Prospects of Future Space Missions

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with special thanks to
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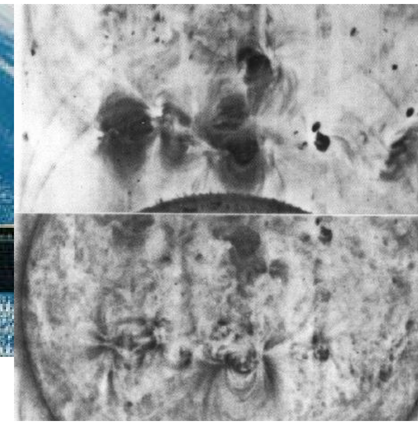
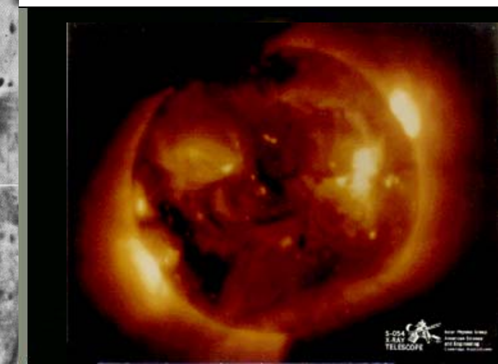
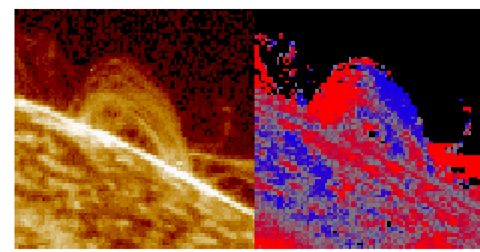
Previous Solar Space Missions

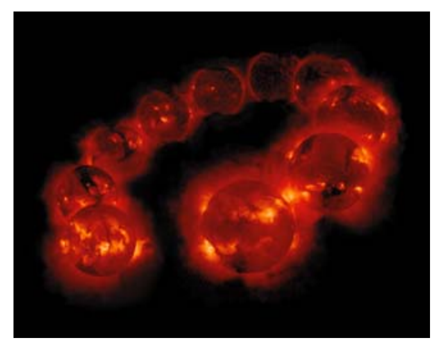
- **OSO 1-8 (1962 - 1978)**
- **Skylab ATM (1973-1977)**
  - Coronal holes
  - Coronal loops
  - Spectral atlas
  - Dynamics of the TR
- **Helios 1 & 2 (1974-80)**
  - Plasma & particles down to 0.3 AU
- **SMM (1980 - 1989)**
  - Solar irradiance (ACRIM)
  - Flares (Hard and Soft X-ray)
  - CME's
  - UV spectral atlas, dynamics
- **Hinotori (1981-1991)**
- **Coronas-I (1994-1995)**
- **Yohkoh (1991-2002)**



Skylab SO54

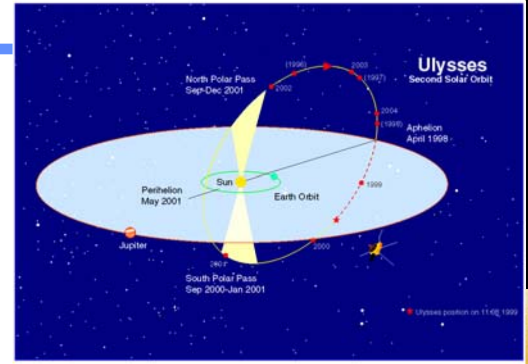


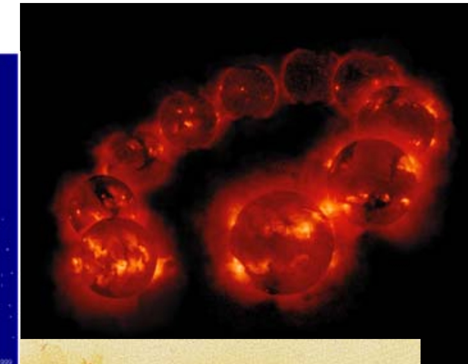


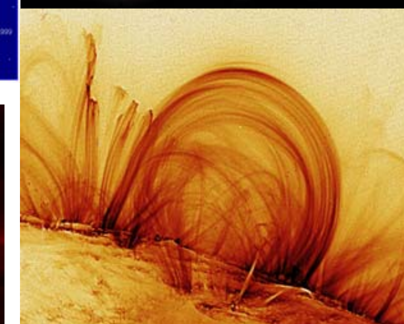


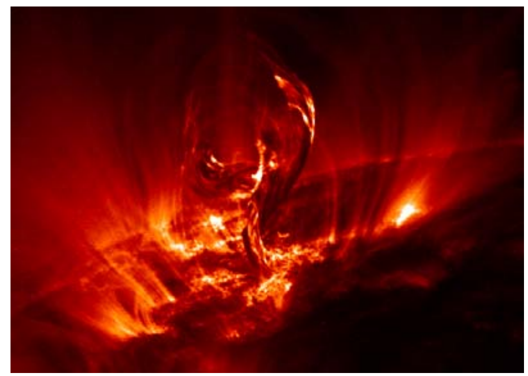
Ongoing Missions

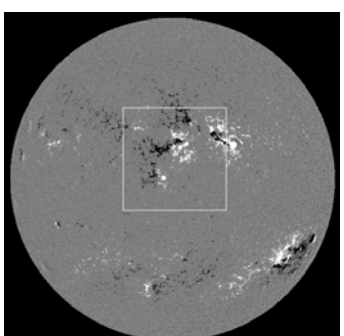
- Ulysses (1990 -)
- SOHO (1995 -)
- ACE (1997 -)
- TRACE (1998 -)
- GENESIS (2001 -)
- CORONAS-F (2001 -)
- RHESSI (2002 -)

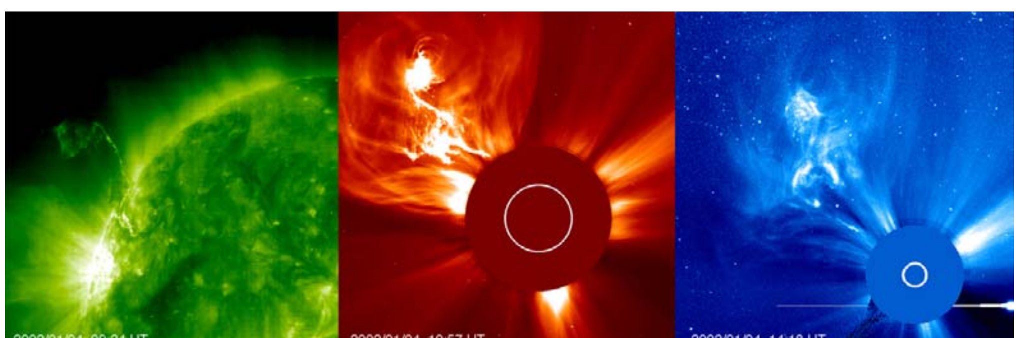


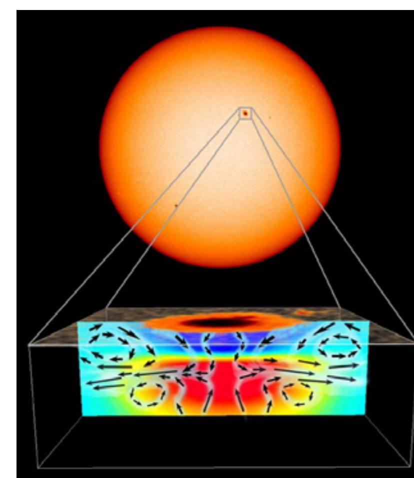










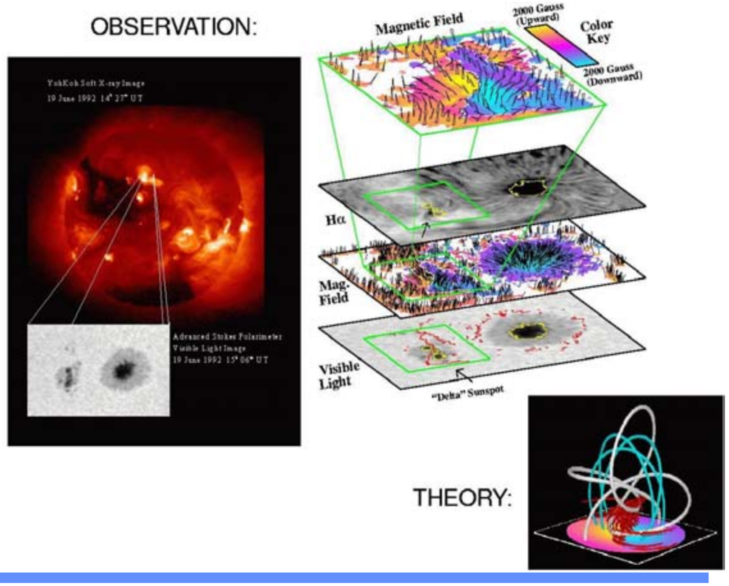


Future Missions

- Solar-B (2005)
- STEREO (2005)
- SDO (2007)
- ASCE (selected for MIDEX Phase A study): 2007?
- Solar Probe (currently in hibernation): 2009+ ?
- Solar Sentinels (LWS): 2009+
- Solar Orbiter (2011/12)
  - Particle Acceleration Solar Orbiter (PASO) (NASA Roadmap 2000)
  - Solar Polar Imager (NASA Roadmap 2000)
- Reconnection and Microscale (RAM) Probe: 2014
- Others
  - Picard (CNES): 2005?
  - Space Solar Telescope (China): 2005?

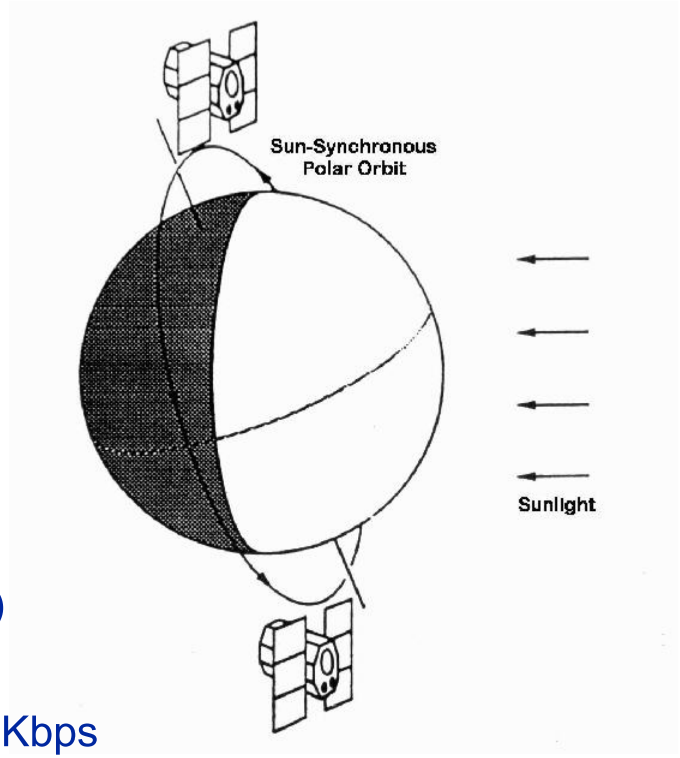
Solar-B Overview

- ISAS mission (with US and UK instrument participation) as follow-on to the highly successful Yohkoh mission
- Target launch date: September 2005
- Mission Goal
  - To advance our understanding of the origin of the outer solar atmosphere, the corona, and of the coupling between the fine magnetic structure at the photosphere and the dynamic processes occurring in the corona.
- Paylod: 3 instruments
  - Solar Optical Telescope (SOT + FPP)
    - 50 cm, 480-650 nm, spectropolarimeter and filtergraph
  - X-ray Telescope (XRT)
    - 2 - 60Å, 1 - 2.5 arcsec resolution, full disk
  - EUV Imaging Spectrograph (EIS)
    - 250 - 290 Å, 1.5 arcsec spatial resolution



Solar-B Mission Characteristics

- Orbit
  - sun-synchronous polar orbit
  - 625 km altitude
  - 97.9º inclination
- Lifetime: > 3 years
- Mass: ~900 kg
- Power: ~1000 Watts
- Attitude control
  - 3-axis stabilized
  - < 1 arcsec stability (<0.02" with tip tilt mirror for SOT)
- Science data rate
  - Average (after JPEG/DOCM compression): 300-500 Kbps
  - Max: 2 Mbps
- Telemetry
  - 4 Gbit onboard storage
  - Playback at 4 Mbps over Kagoshima and other high latitude stations (possibly including ESA station in Kiruna or Svalbard)



Solar-B: Artists’ Impression

Solar-B Structural Model

Solar-B: SOT/FPP Science Goals

- Magnetic Flux Transport
  - Observe how magnetic flux emerges, disperses & disappears from the solar surface, including weak intranetwork fields (B<400G)
  - Determine whether magnetic field is generated in or near the surface: fast dynamo action
- Scales of Convection
  - Investigate the relationship of granulation, mesogranulation, and supergranulation
- Sunspots and Active Regions
  - Measure the vector magnetic field of sunspots and plage areas
  - Observe the formation, dynamics & decay of entire active regions
- Upper Atmospheric Connections
  - Determine the role of the surface magnetic field on the structure and dynamics of the outer atmosphere
- Solar Cycle Evolution
  - Measure the effect of active regions on the solar cycle irradiance modulation

Solar-B: Solar Optical Telescope (SOT)

PI: Takeo Kosugi (ISAS)

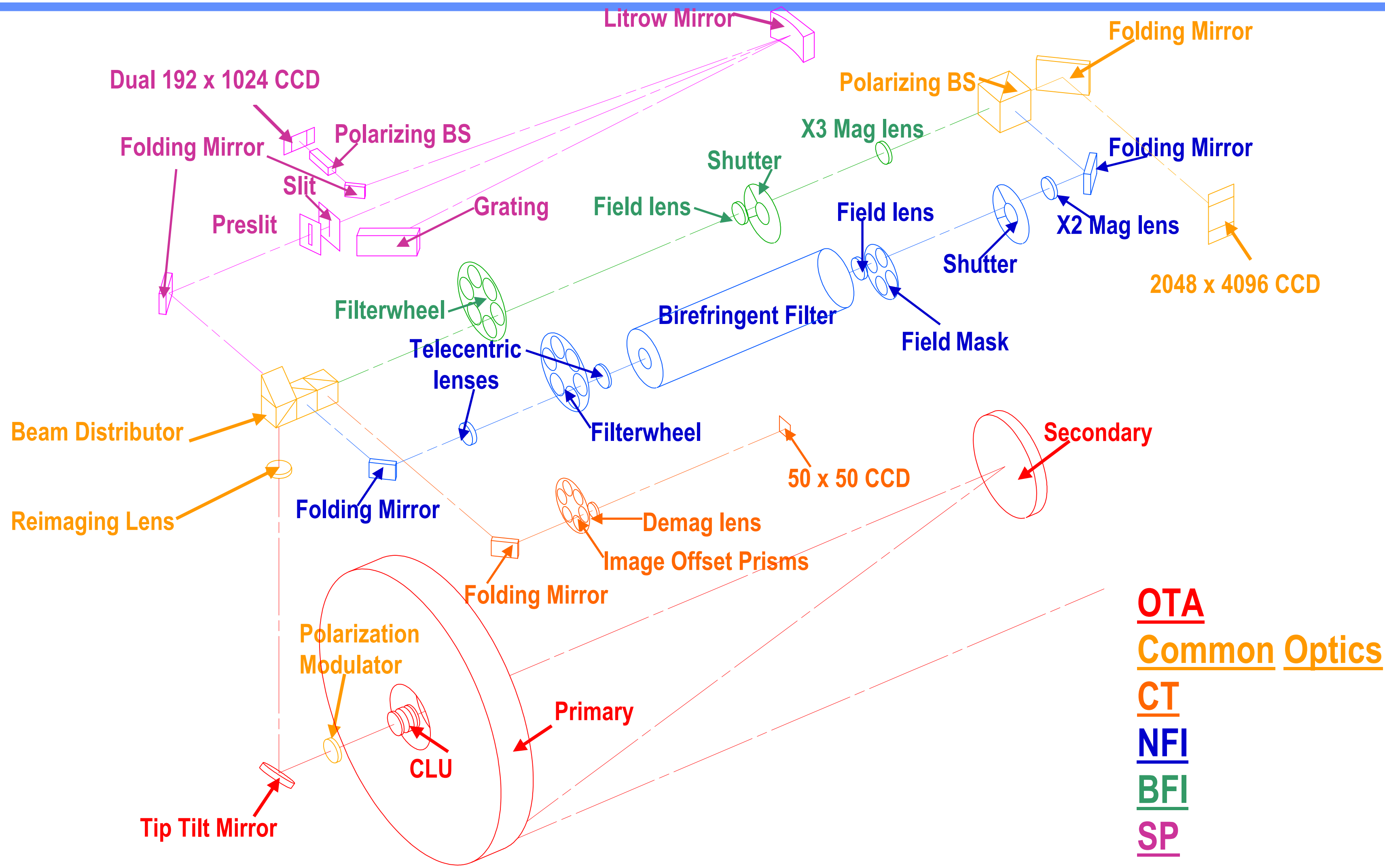
- 0.5 m Gregorian for 0.2” spatial resolution @ 5000Å
- Preserves image quality from 3880 – 6600 Å
- Axisymmetric design for minimal instrumental polarization
- Polarization Modulator Unit: rotating waveplate before any oblique reflection
- Tip/Tilt mirror: PZT-actuated folding mirror for image stabilization (<0.02 arcsec over range 0.02 – 20 Hz)

Solar-B: Focal Plane Package (FPP)

PI: Alan Title (LMSA)

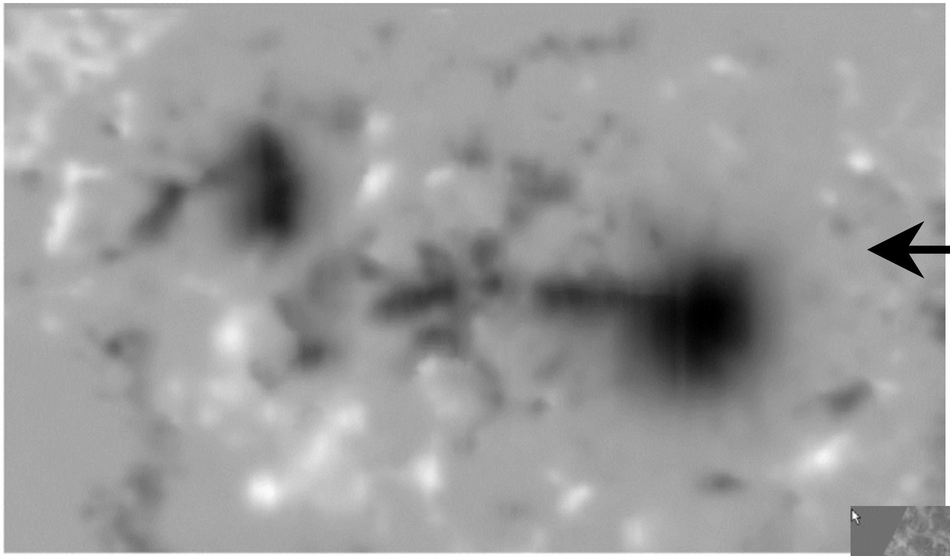
- BFI: Broadband Filter Imager
  - Filtergrams with highest spatial and temporal resolution (interference filters)
  - Data similar to G-band movies from La Palma, with perfect seeing.
  - FOV: 216” × 108” max (partial readout and subarea selection for faster cadences also possible)
  - Common focal plane with NFI: 2048 × 4096 CCD: 0.053” pixels
- NFI: Narrowband Filter Imager
  - Tunable birefringent filter (8-calcite wide-field elements): ~0.1Å bandwidth
  - Vector magnetograph
  - Data similar to the SOUP filter images from La Palma, with higher sensitivity and spatial resolution.
  - FOV selectable via focal plane mask:
    - 320” × 160” max (some vignetting in corners) for filtergrams
    - 160” × 160” (and smaller subfields) for Dopplergrams and magnetograms
  - Common focal plane with BFI: 2048 × 4096 CCD: 0.08” pixels
- SP: Spectro-Polarimeter
  - Fe I 6301/6302Å lines: dual line dual polarization spectra for high precision Stokes polarimetry (<0.1%)
  - Littrow design (off-axis parabolic mirror)
  - Data similar to HAO ASP, with much higher spatial resolution.

Solar-B: Optical Schematic of SOT/FPP



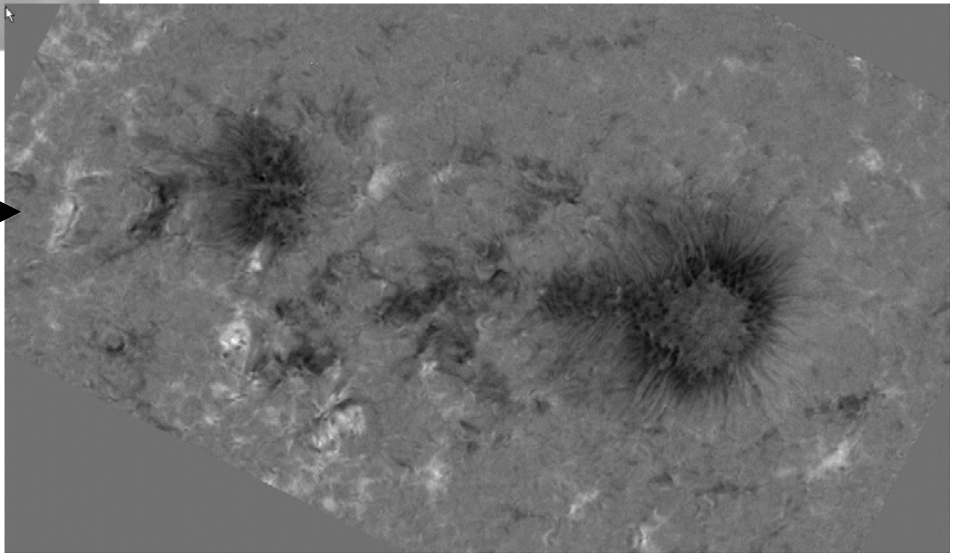
OTA
Common Optics
CT
NFI
BFI
SP

Comparison of ASP and Filtergraph Magnetograms



Stokes Longitudinal Magnetogram obtained with the Advanced Stokes Polarimeter at the Dunn Solar Telescope (NSO/Sacramento Peak) on 13 May 1998, created from a sequence of Stokes spectra. Vector magnetic field and Doppler shift maps with high accuracy are also produced from this data.

Longitudinal Magnetogram obtained with the SOUP Filter at the Swedish Vacuum Solar Telescope (La Palma) on 13 May 1998, constructed from a pair of filtergrams.



Solar-B will make vector field maps with accuracy and sensitivity similar to the ASP's and with spatial resolution similar to these filtergrams'.

Solar-B: X-ray Telescop (XRT)

PI: Leon Golub (SAO)

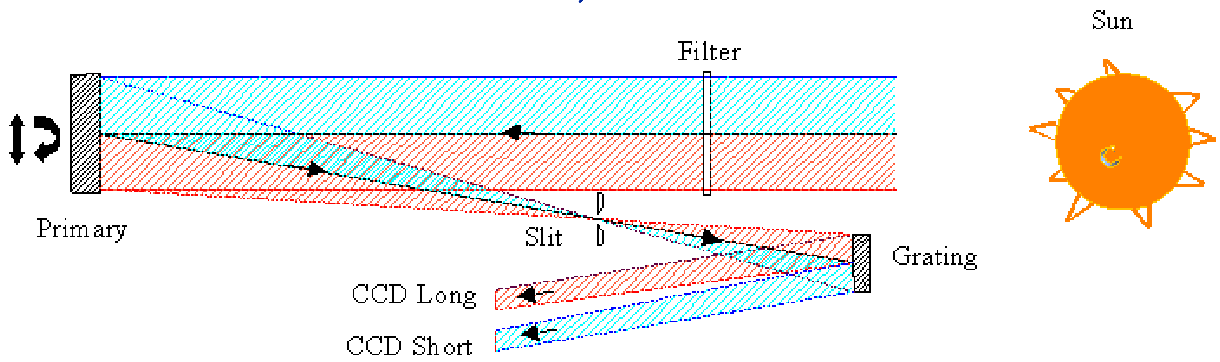
- High resolution broadband imaging of the corona
- Relationship: photospheric driving and coronal dynamics
- Follow-on of Yohkoh/SXT
  - Broader temperature response
  - Higher resolution (2k×2k CCD ⇒ 1arcsec pixels)

XRT Properties	
Effective Area @ 0.5 keV	1 cm^2
Temperature Range	6.1 - 7.5 (Log T_e)
Temperature Resolution	0.2 (Log T_e)
FOV	34 $arcmin^2$
Spatial Resolution	1.0"/pixel
Temporal Cadence	0.5 - 10 sec
Number of X-ray filters	9

Solar-B: EUV Imaging Spectrometer (EIS)

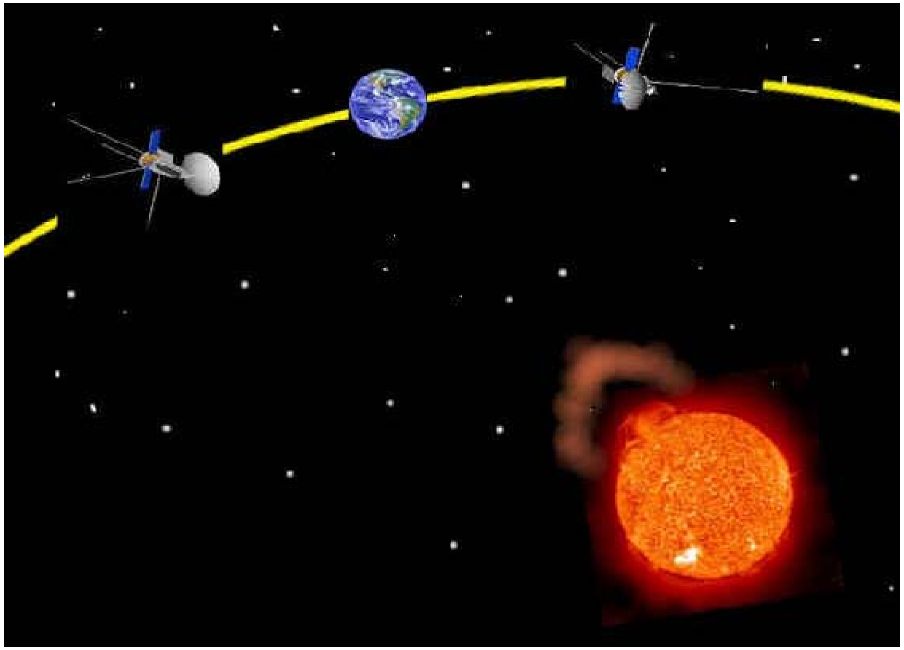
PI: Len Culhane (MSSL)

- High throughput imaging spectroscopy (0.1 < T < 20 MK)
- 15 cm diameter primary
- Two wavelength bands of 40 Å width, each with its own optimized CCD detector
  - Short wavelength centered at 190 Å
  - Long wavelength centered at 270 Å
- Spatial resolution: 2 arcsec (1 arcsec pixels)
- Spectral resolution: ±3 km/s (line centroids)
- Temporal resolution: 10 s in AR, < 1 s in flares



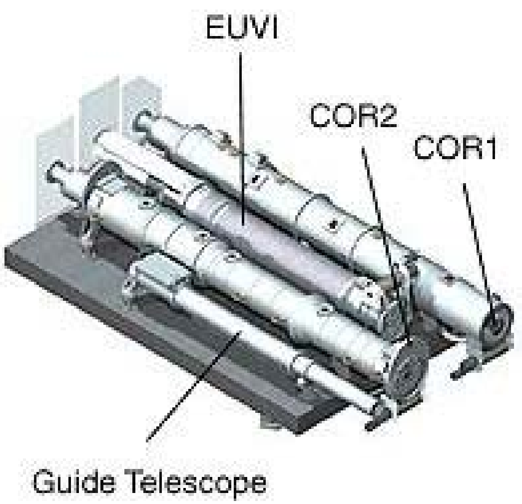
STEREO

- **Principal Science Objective**
  - Origin and consequences of CMEs
- **Mission Profile**
  - 2 identical S/C
    - Mass: 556 kg each (dry mass)
    - Volume: 1.2 m x 2.0 m x 1.5 m
    - Power: 540 W
  - one drifting ahead of Earth, one behind (22.5º per year)
  - Mission life: > 2 years
  - Launch: November 2005
  - Launch Vehicle: Delta 2925-10L

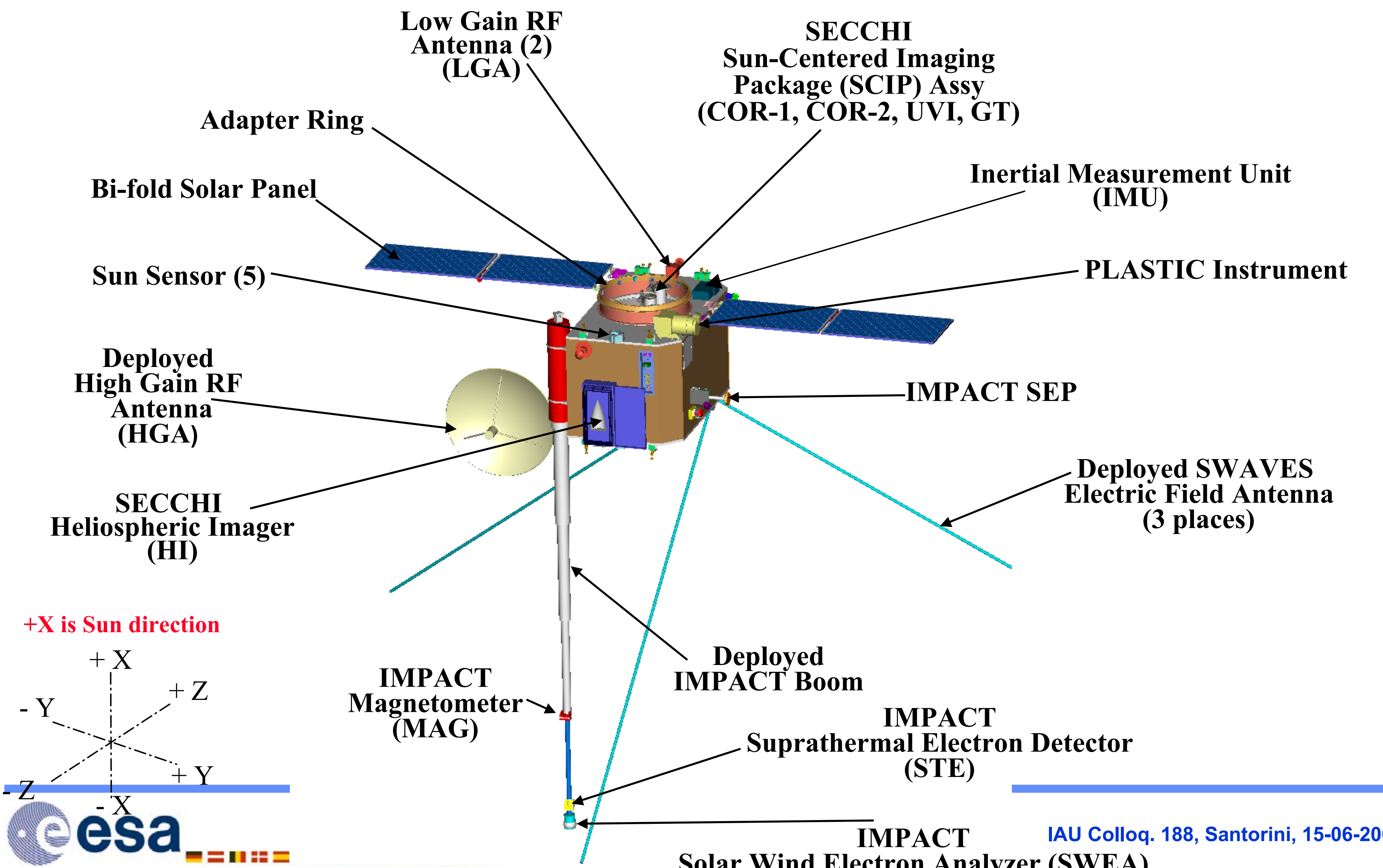


STEREO Payload

- SECCHI
  - 2 white-light coronagraphs (1.25-4 $R_\odot$, 2-15 $R_\odot$)
  - full sun EUV imager
  - heliospheric imager: externally occulted coronagraph imaging the heliosphere from 12 $R_\odot$ to beyond Earth's orbit
- SWAVES
  - Interplanetary radio burst tracker
- IMPACT
  - 3-D distribution and plasma characteristics of energetic particles and local vector magnetic field
- PLASTIC
  - Plasma characteristics of protons, alpha particles, and heavy ions



STEREO Spacecraft



Solar Dynamics Observatory (SDO)

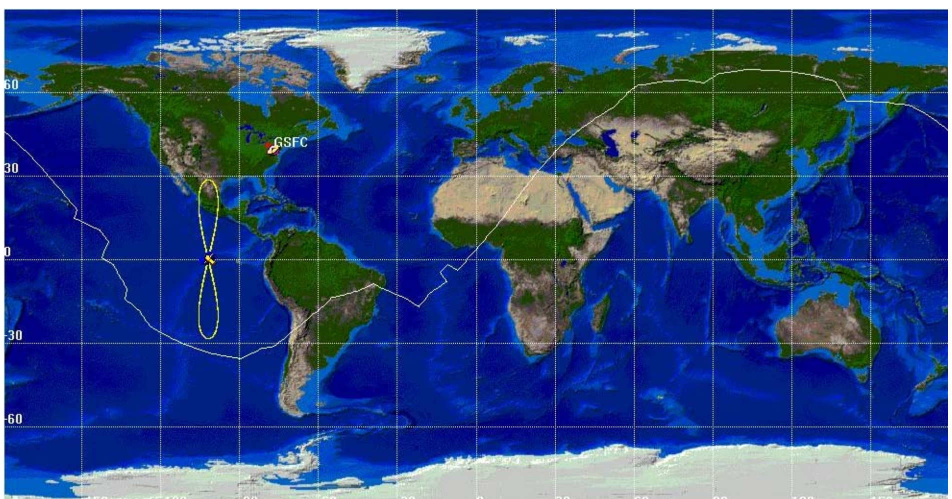
- 1st Space Weather Research Network mission in NASA's Living With a Star (LWS) program
- LWS Goal
  - Develop the scientific understanding necessary to effectively address those aspects of the connected Sun-Earth system that directly affect life and society.
    - How and why does the Sun vary?
    - How does the Earth respond?
    - What are the impacts on life and society?
- SDO Goal
  - Understand, ideally to the point of predictability, the solar variations that influence life on Earth and humanity's technological systems by determining how the Sun's magnetic field is generated and structured and how this stored magnetic energy is converted and released into the heliosphere and geospace in the form of solar wind, energetic particles, and variations in solar irradiance.

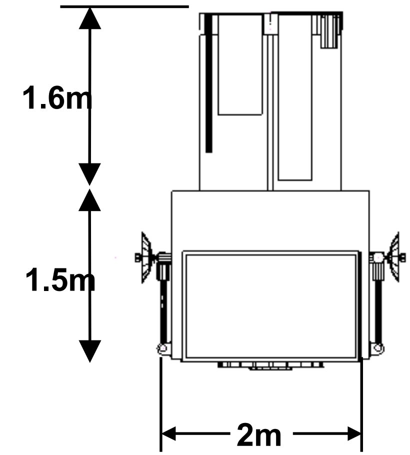
SDO Mission Objectives

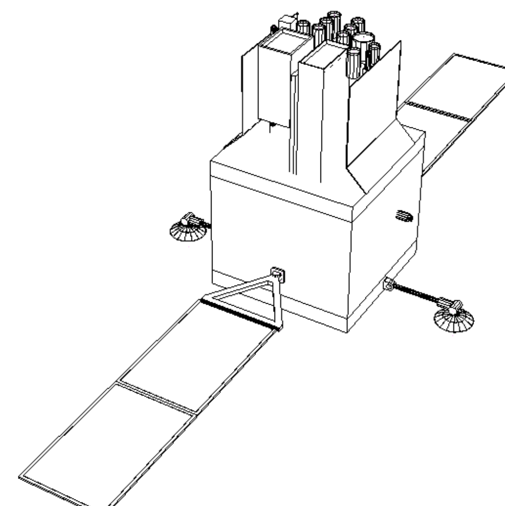
- Determine how and why the Sun varies
  - Understand three interlinked magnetic processes that act on different time scales:
    - Solar cycle
    - Active regions
    - Small-scale magnetic elements
- Improve understanding of how the Sun drives global change and space weather
  - electromagnetic radiation
  - energetic particles
  - solar wind plasma

SDO Mission Profile

- Target launch date: August 2007
- Mission life: 5 years (10 years consumables)
- 3-axis stabilized S/C, Mass ≈ 1300 kg (250 kg P/L)
- Orbit: geosynchronous, inclined at 28.5º
  - 1 ground station → simple and cheap operations
  - continuous contact
  - extremely high data rate (150 Mbit/s)







SDO Payload

SDO AO: - released 18 Jan
- due date 24 April
Selection: Aug/Sep (goal)

- Highest priority
  - Helioseismic and Magnetic Imager (MDI+)
    - *4k × 4k detector, full disk, high resolution, continuous obs.*
  - Atmospheric Imaging Assembly (EIT/TRACE+)
    - *4k × 4k detector*
    - *full disk (EIT) high resolution (TRACE)*
    - *4-8 channels simultaneously at 10 sec cadence*
  - EUV Irradiance Spectrometer (10-1200 Å with 1 Å resolution)
  - White-Light Coronagraph (LASCO+)
  - Total solar irradiance (VIRGO+; if not available from other sources)
- High priority
  - UV/EUV Imaging Spectrometer (SUMER/CDS+)
  - Photometric Imaging Telescope
  - Vector Magnetograph

Solar Orbiter: Background

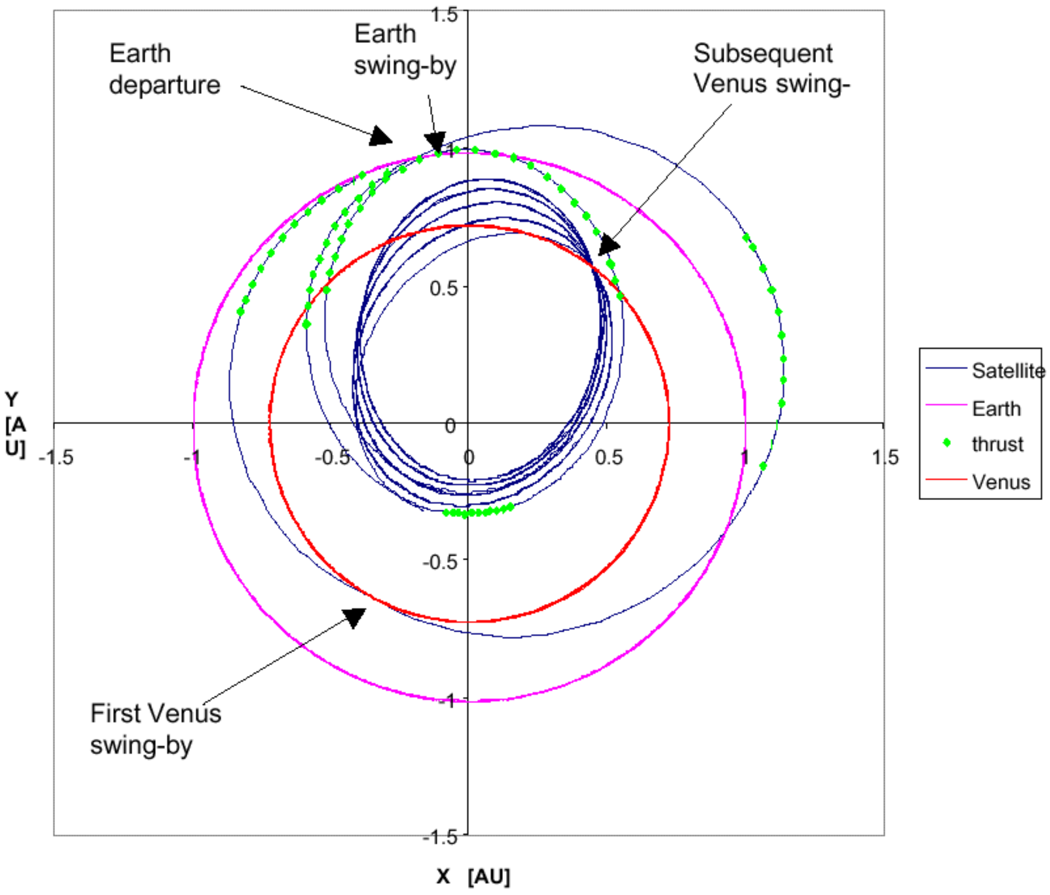
- "Tenerife Crossroads" Workshop (March 1998) Resolution
  - "Launch a Solar Orbiter, as ESA's F2 mission, with possible international participation, around 2007; there are two main candidates for this, namely a mission approaching the Sun to 30 solar radii, and a polar orbiter at about 0.5 AU.
- ESA Pre-Assessment Study conducted in 1999
- Solar Orbiter proposed as a Flexi-mission in 2000 by E. Marsch et al.
- ESA "delta"-Assessment Study conducted in 2000
- Solar Orbiter selected by ESA's SPC in October 2000 for launch after BepiColombo (2008-2013 timeframe)
- Solar Orbiter re-confirmed by ESA's SPC in May 2002 for implementation with BepiColombo as a single project in 2011/2012
- ESA's SSAC also encouraged further international collaborations, specifically involvement of NASA in Solar Orbiter as part of the ILWS program, linked to European participation in other LWS/STP elements.
- Industrial study to start in fall 2002, tightly coupled to BepiColombo

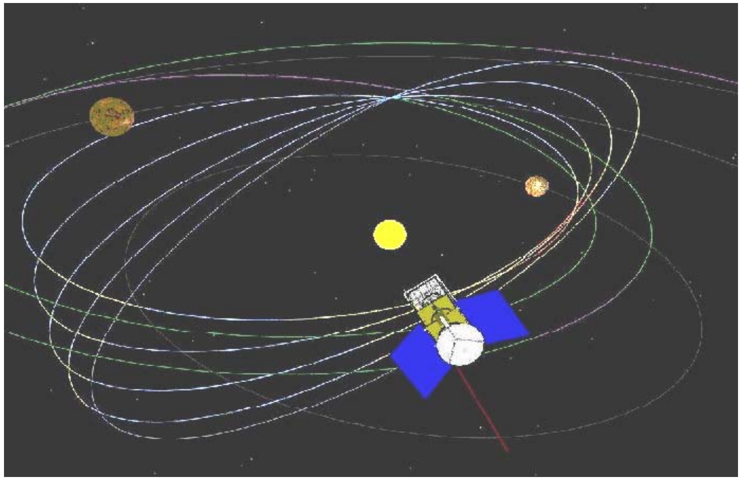
Solar Orbiter: New Perspectives

- explore the uncharted innermost regions of our solar system
- study the Sun from close-up (45 solar radii or 0.21 AU)
- fly by the Sun tuned to its rotation and examine the solar surface and the space above from a co-rotating vantage point
- provide images of the Sun's polar regions from heliographic latitudes as high as 38°

Solar Orbiter: Novel Orbital Design

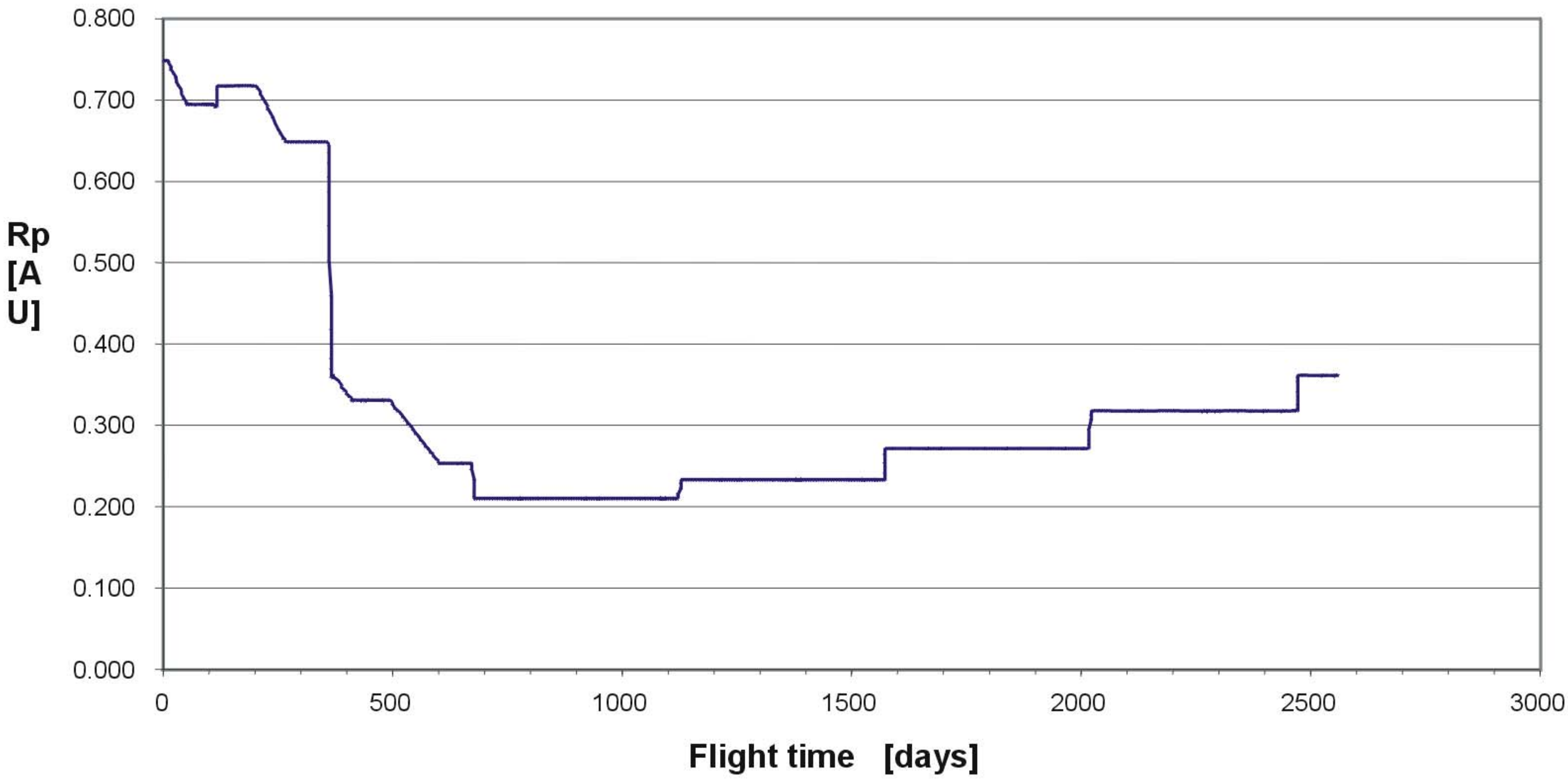
XY-plane trajectory plot including extended



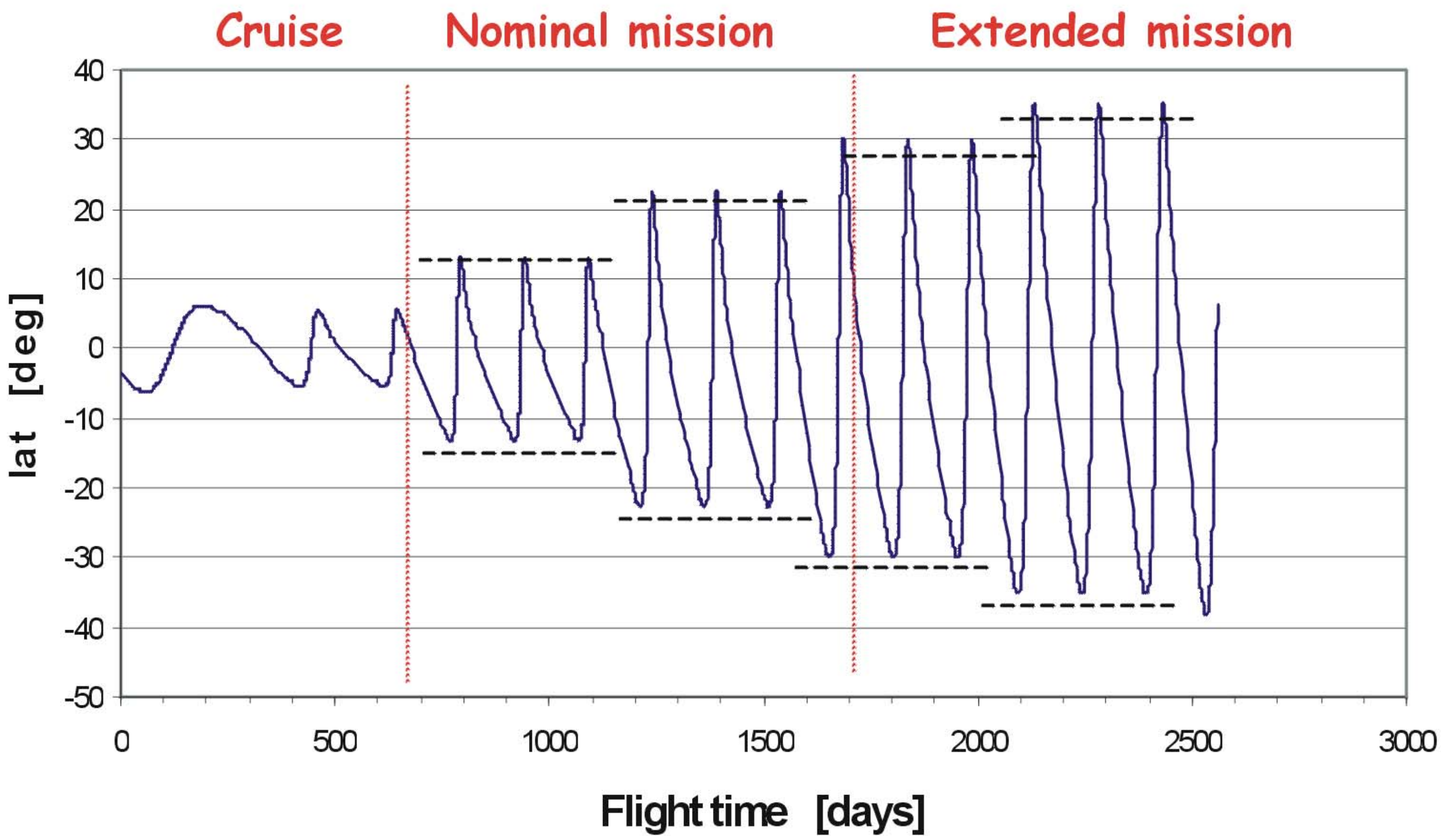


- closer to the Sun
- out of the ecliptic

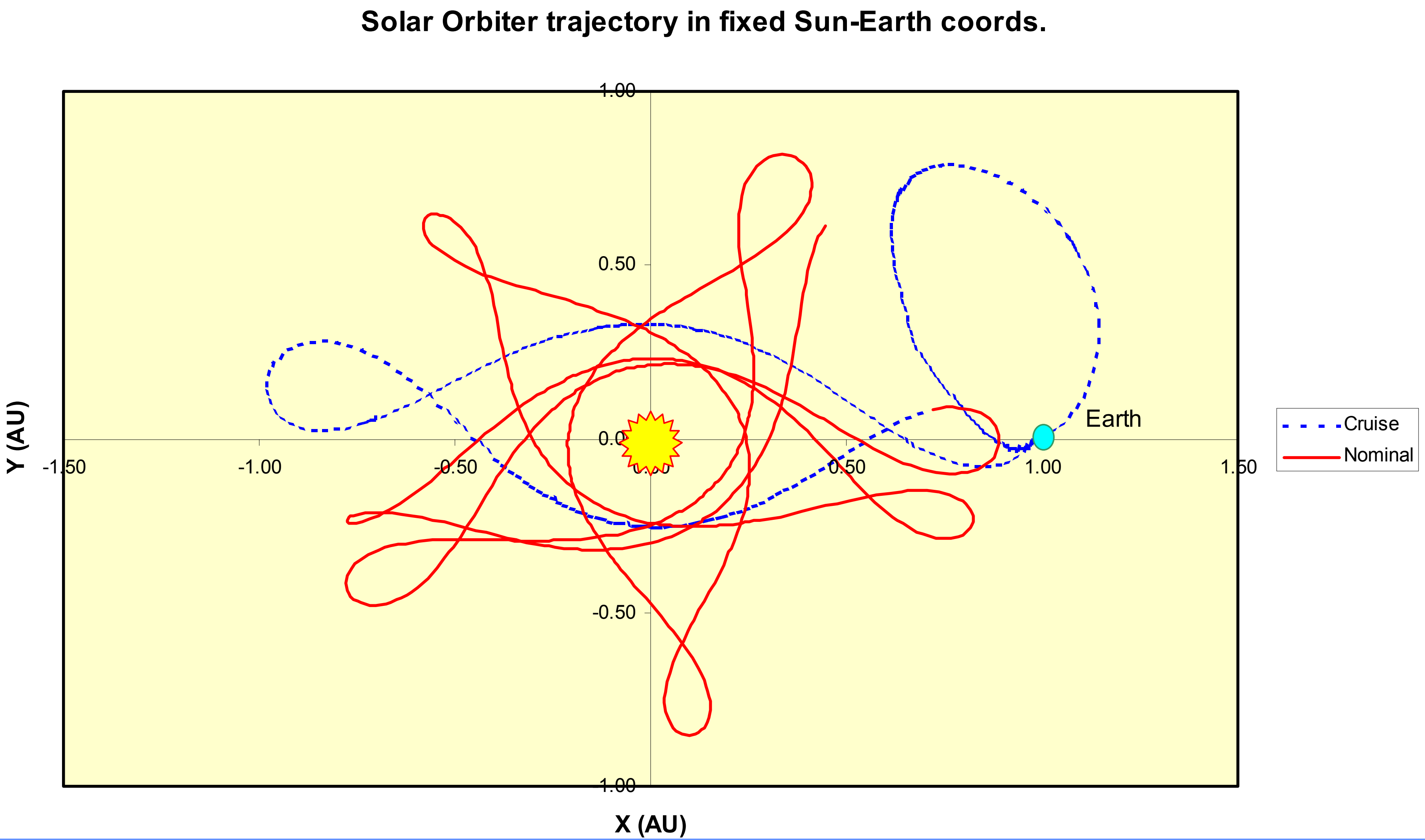
Solar Orbiter: S/C Perihelion Distance



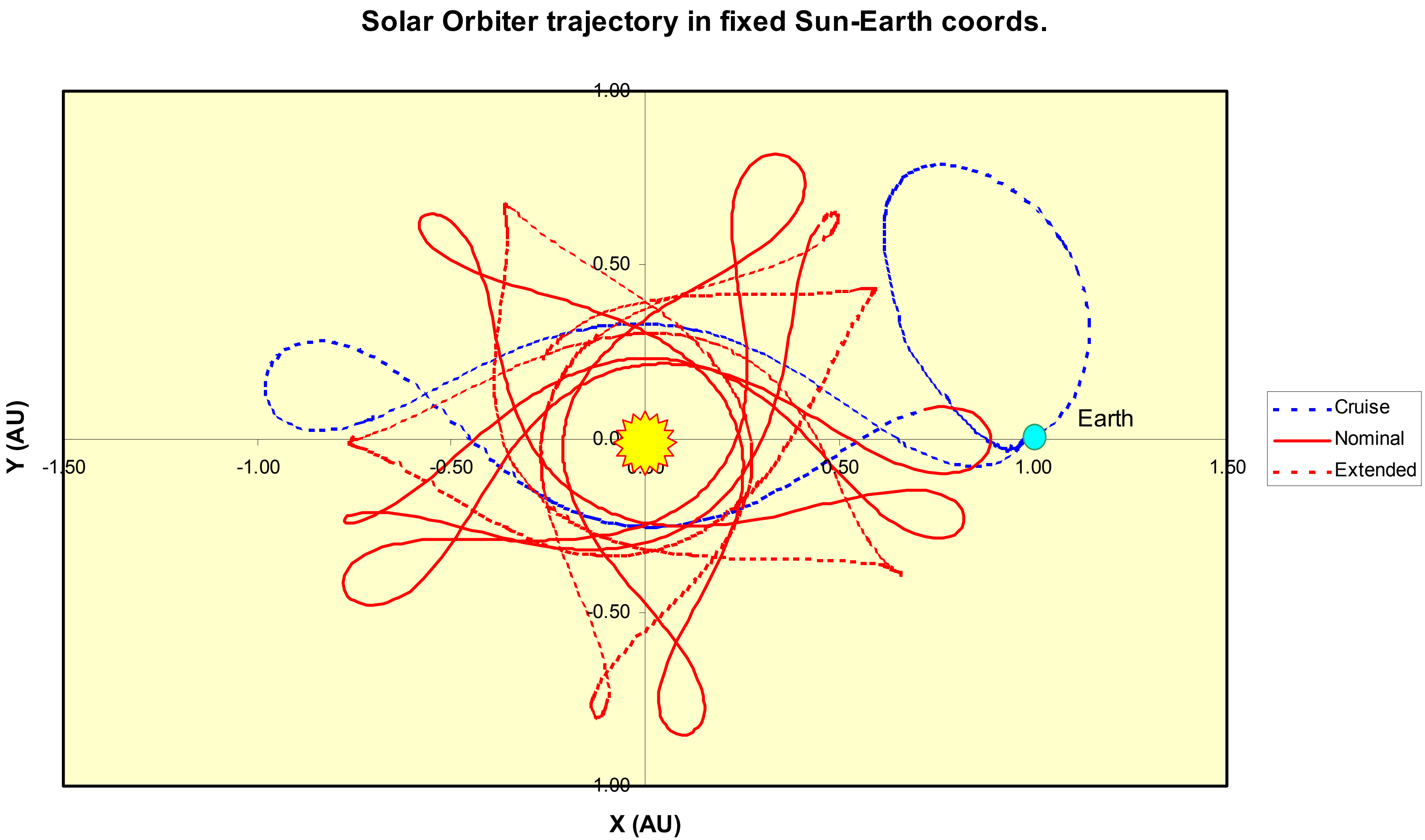
Solar Orbiter: S/C Heliographic Latitude



Solar Orbiter Trajectory

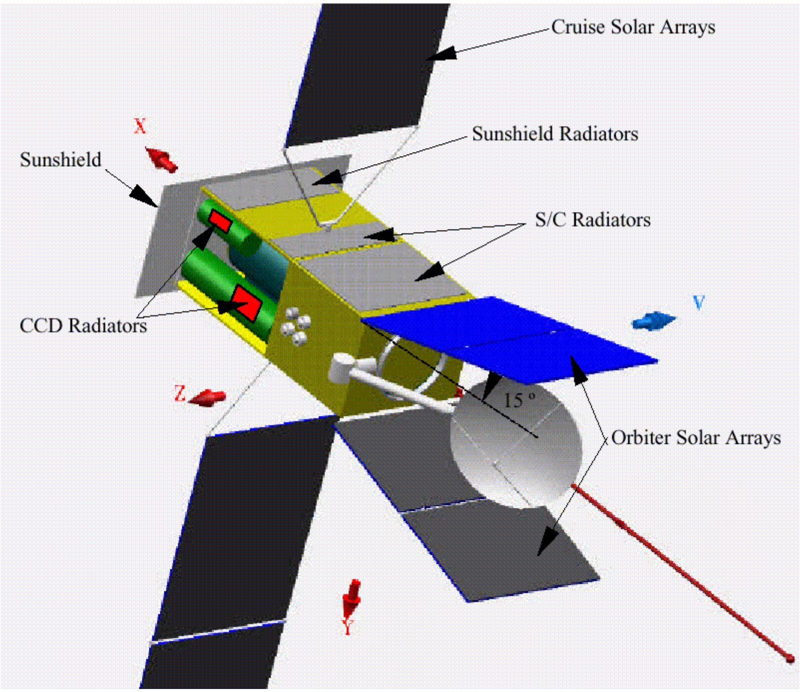


Solar Orbiter Trajectory



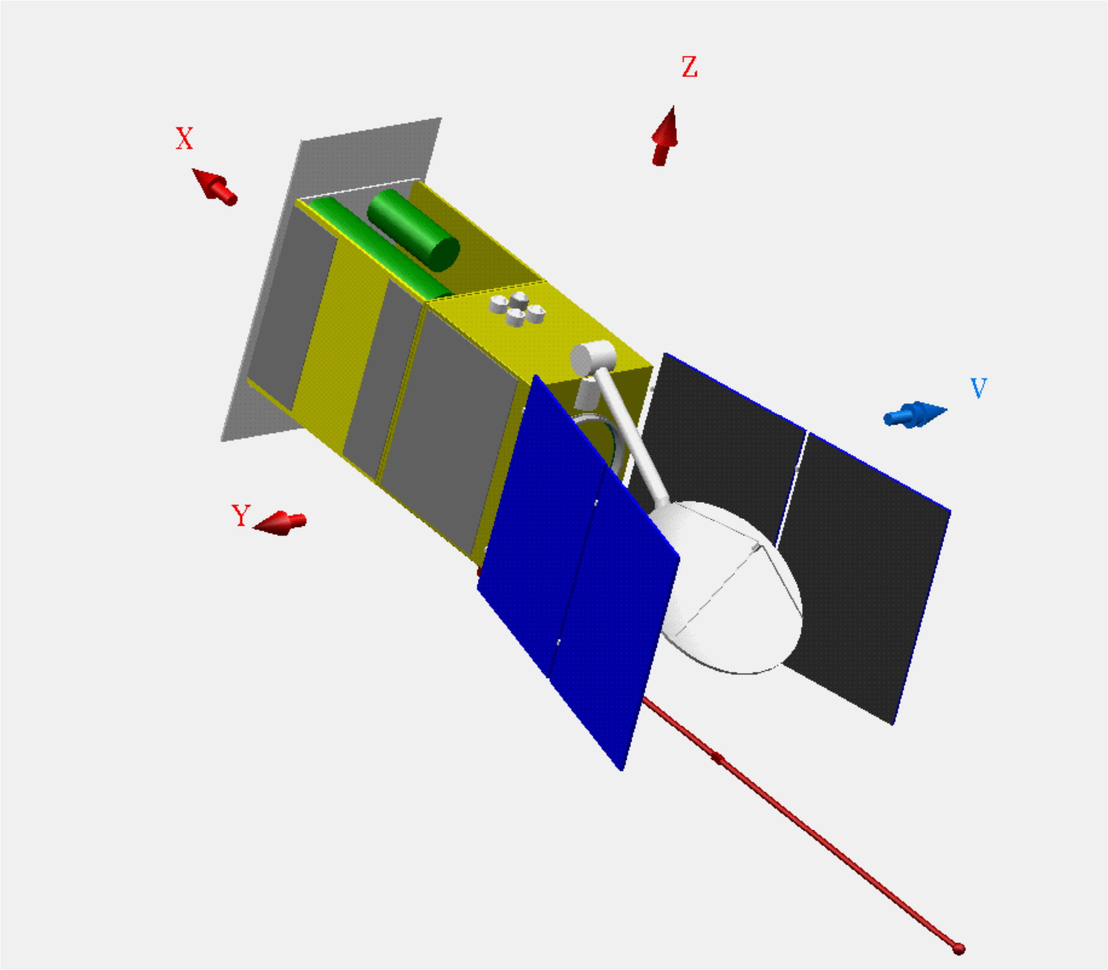
Solar Orbiter: Spacecraft Overview

- Total mass: 1310 kg (130 kg P/L)
- Dimensions: 3 m x 1.2 m x 1.6 m
- 3-axis stabilized
  - pointing stability better than 3 arcsec / 15 min
- Solar Electric Propulsion (SEP):
  - 4 x 0.15 N stationary plasma thrusters
- Deployable and rotatable Cruise solar arrays, jettisoned after last SEP thrusting

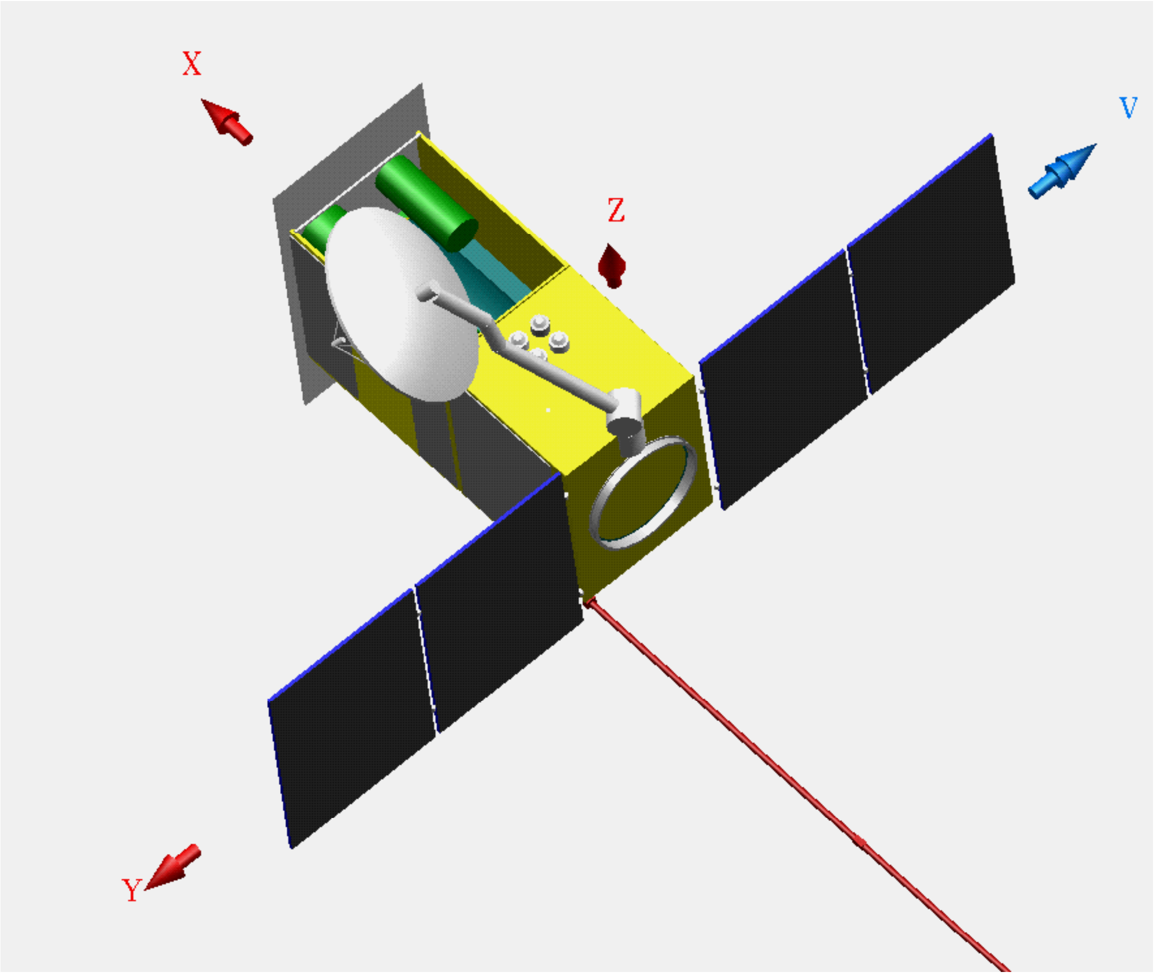


- Deployable and tiltable Orbit solar arrays
  - 16% GaAs cells, 84% OSR.
- 4 X-band LGAs, omni coverage, for TT&C.
- One Ka-band HGA, 1.5 m dia., for telemetry after Cruise.

Solar Orbiter in Observation Mode



Solar Orbiter in Data-dump Mode



Solar Orbiter: Remote-sensing Instruments

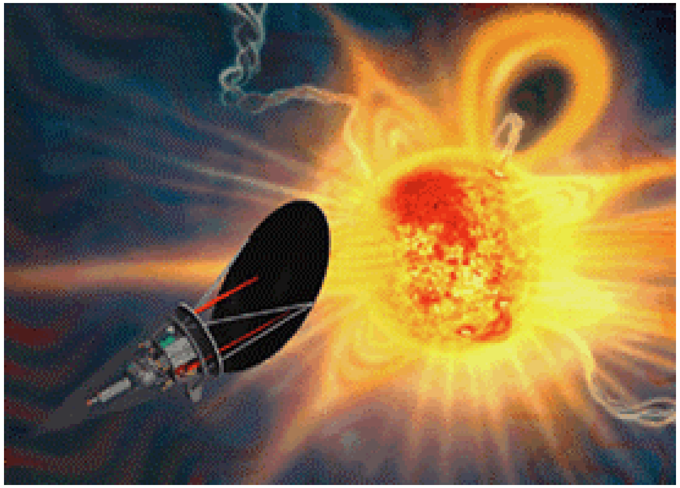
Instrument	Mass kg	Power W	kb/s
Visible Light Imager & Magnetograph (VIM)	26	25	20
Extreme UV Spectrometer (EUS)	22	25	17
Extreme UV Imager (EUI)	36	20	20
UV & Visible Light Coronagraph (UVC)	17	25	5
Radiometer (RAD)	4	6.5	0.5

Solar Orbiter: Heliospheric *in-situ* Package

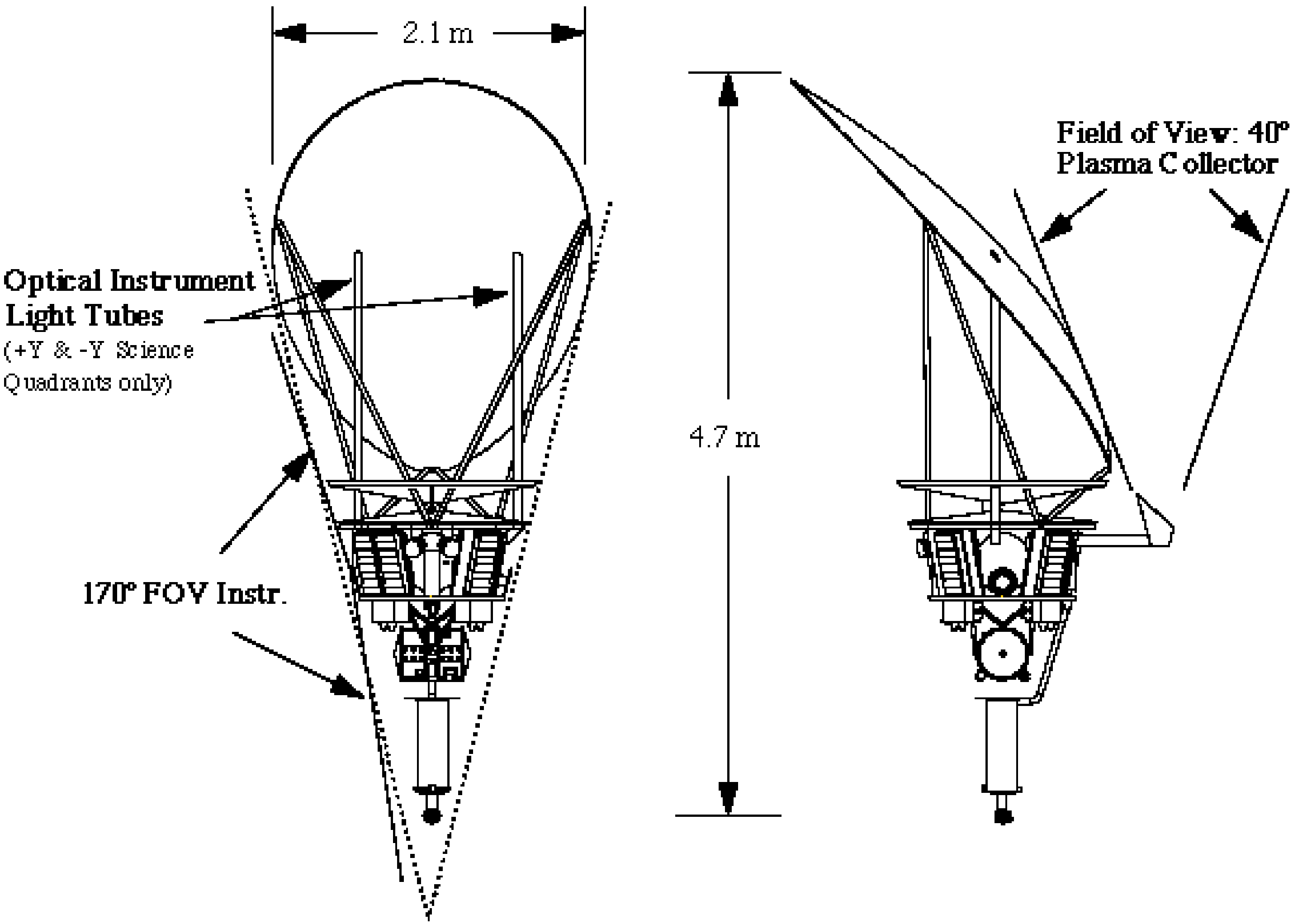
Instrument	Mass kg	Power W	kb/s
Solar Wind Plasma Analyser (SWA)	6	5	5
Radio & Plasma Waves Analyser (RPW)	10	7.5	5
Coronal Radio Sounding (CRS)	0.2	3	0
Magnetometer (MAG)	1	1	0.2
Energetic Particle Detector (EPD)	4	3	1.8
Dust Detector (DUD)	1	1	0.05
Neutral Particle Detector (NPD)	1	2	0.3
Neutron Detector (NED)	2	1	0.15

Solar Probe

- Primary Science Objective
  - Understand the processes that heat the solar corona and produce the solar wind.
- Mission Profile
  - Arrive at the Sun at polar trajectory perpendicular to Sun-Earth line
  - Perihelion at 4 $R_\odot$ at solar equator
  - Distance over poles: 8 $R_\odot$
- Payload: *Mass: 19 kg, Power: 16 W*
  - Remote Sensing Instruments
    - Magnetograph/Helioseismograph
    - XUV imager
    - All-sky, 3-D coronagraph imager
  - In-situ Instruments
    - Vector magnetometer
    - Solar wind ion composition and electron spectrometer
    - Energetic particle composition spectrometer
    - Plasma wave sensor
    - Fast solar wind ion detector



Solar Probe

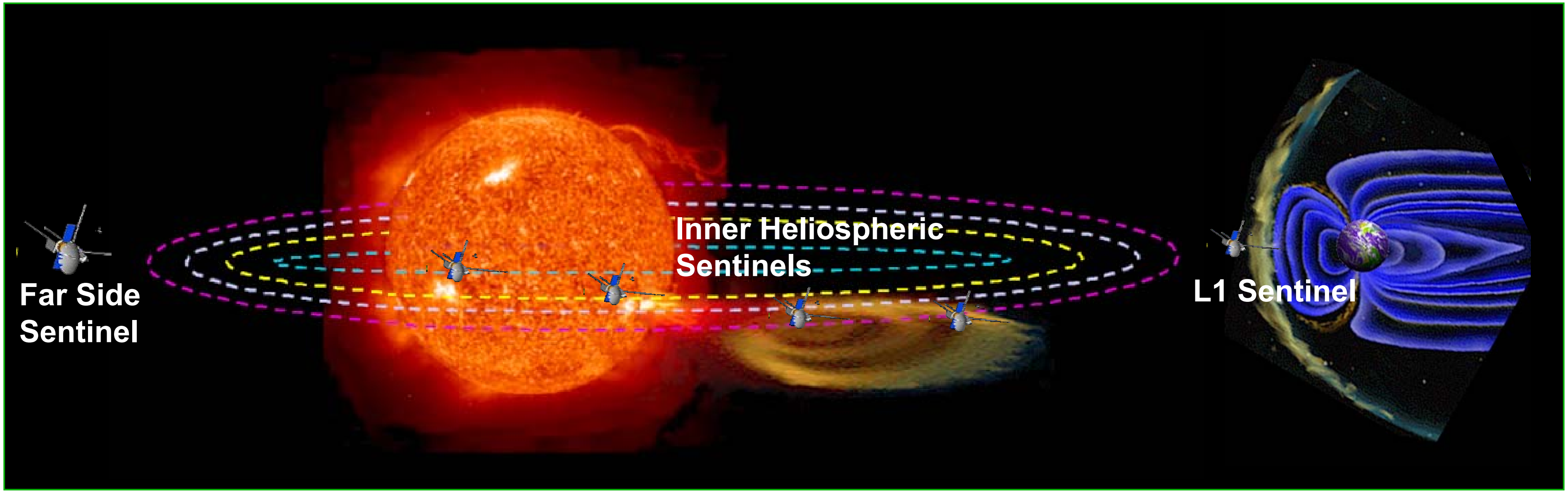


2.1 m
4.7 m
Optical Instrument
Light Tubes
(+Y & -Y Science
Quadrants only)
170° FOV Instr.
Field of View: 40°
Plasma Collector

Solar Sentinels

- Set of notional missions to investigate the physics of the interplanetary medium that links solar processes to Earth's environment
- Objectives
  - Global characterization of the heliosphere
  - Transit and evolution of geoeffective structures
  - Connecting geoeffective structures to solar features/activity
  - Location and mechanism of energetic particle release and acceleration

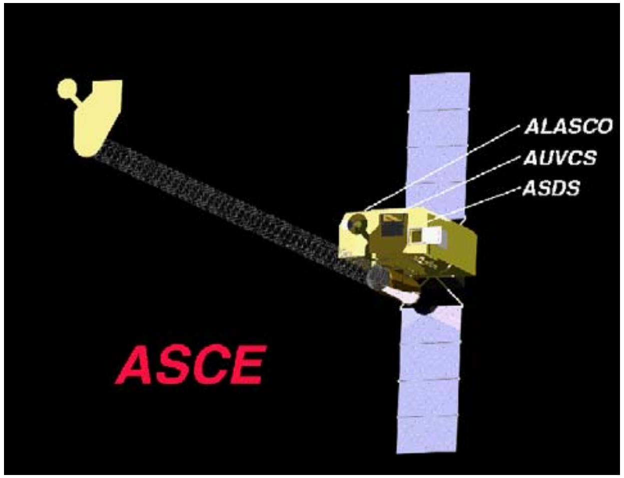
Solar Sentinels



- Far Side Sentinel - 3-axis stabilized spacecraft
- Inner Heliospheric Sentinels - 4 spinning s/c in 0.5-0.95 AU heliocentric orbits
- L1 Sentinel - Spinning s/c in L1 Halo orbit

Advanced Spectroscopic and Coronagraphic Explorer (ASCE)

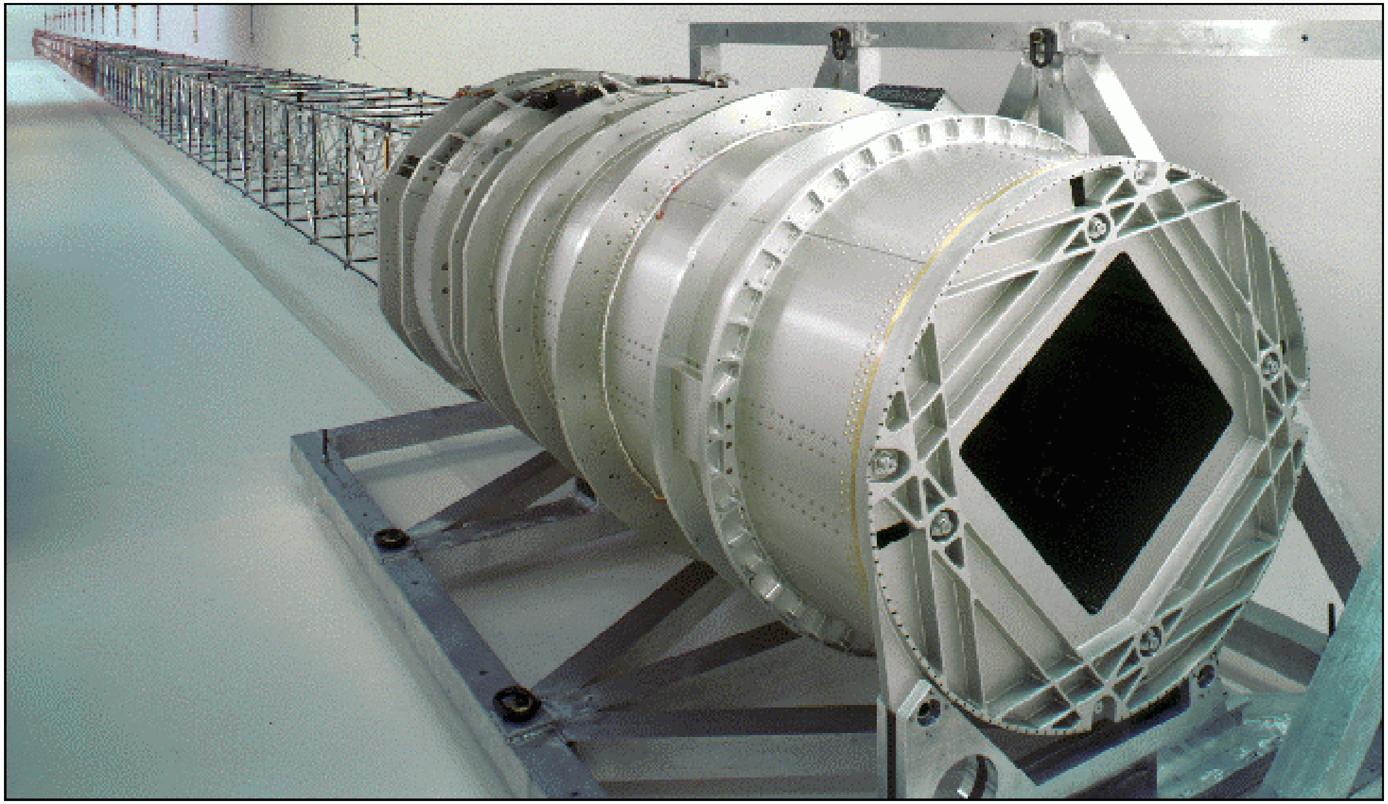
- PI: John Kohl (SAO)
- Selected by NASA in April '02 for detailed mission concept study (MIDEX program)
- Scientific Objectives
  - Heating and acceleration of the solar wind
  - Magnetic energy transport into corona
    - Coronal heating
    - Mass flows
  - Heating and acceleration of CMEs



- Key element: Deployable External Occulter Module (DEOM)
  - 14.7 m from telescope mirrors
  - Factor 8.5 increase in effective telescope mirror area
  - Decrease in scattered light
  - Allows observations lower corona

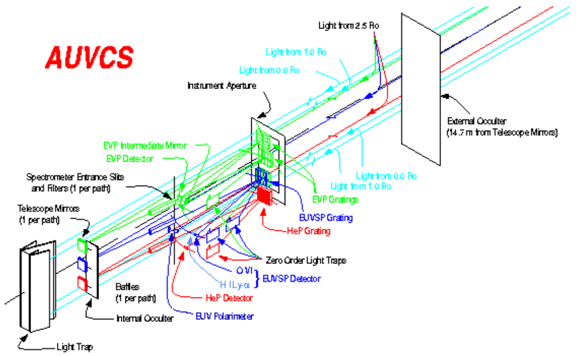
ASCE Deployable External Occulter

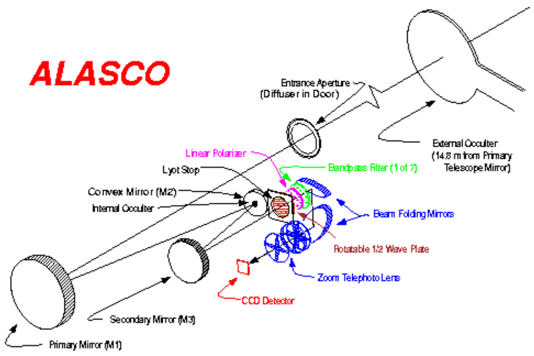
SRTM ADAM – View from Base

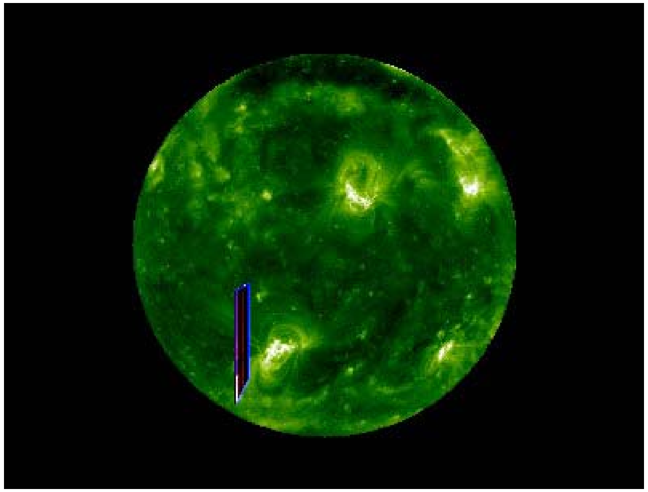


ASCE Science Payload

- Advanced UltraViolet Coronagraph Spectrometer (AUVCS)
  - 1.15-10 $R_\odot$
  - H I Ly α, H I Ly β, O VI doublet at 1030 Å, He II 304 Å
- Advanced Large Aperture Solar Coronagraph (ALASCO):
  - Visible light polarimetry: 1.1 – 10 $R_\odot$
  - Externally and internally occulted mirror coronagraph
- Advanced Solar Disk Spectrometer (ASDS)
  - Off-axis parabolic telescope + asymmetric Czerny-Turner spectrograph
  - Fast 2-D raster (1 arcsec resolution): 10 sec cadence
- 4k x 4k detectors

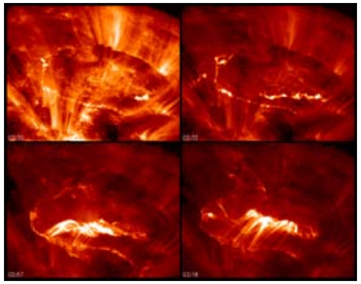






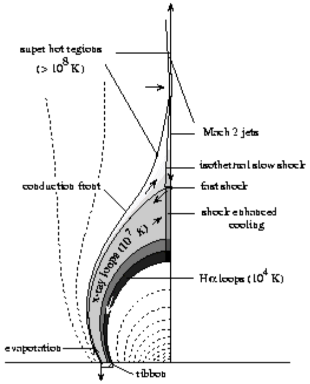
Reconnection and Microscale Probe (RAM)

❑ Science Objectives



- ➢ What are the mechanisms that lead to reconnection?
- ➢ What micro-scale instabilities lead to global effects?
- ➢ Where are the regions of particle acceleration?
- ➢ Where are the reconnection regions and what is their topology?
- ➢ How do magnetic stresses form and release in the corona?

❑ Mission Description

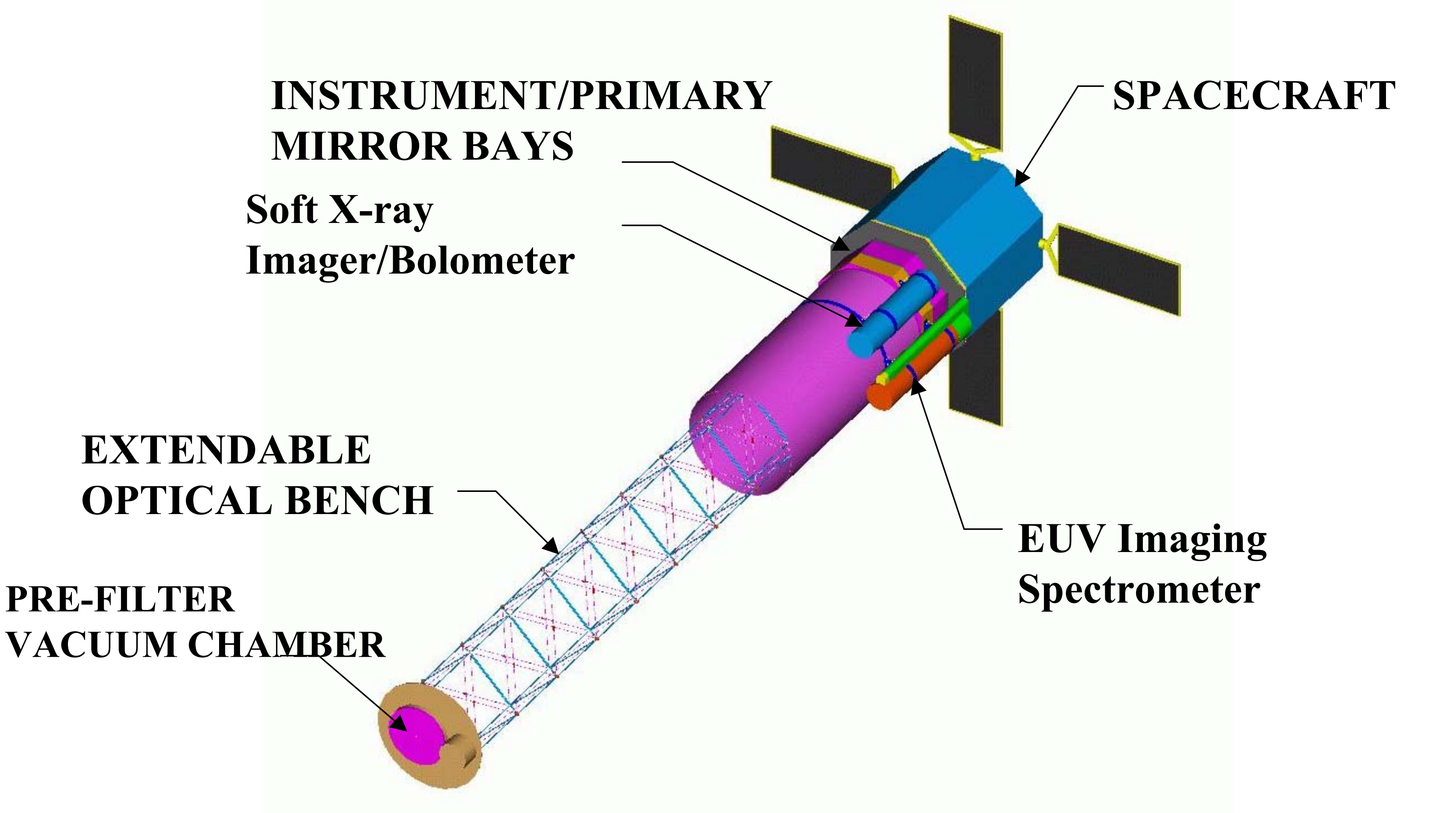


- ➢ Continuous solar observations from geostationary orbit
- ➢ NASA STP-class mission
- ➢ Mission lifetime: 3 years (launch 2014?)

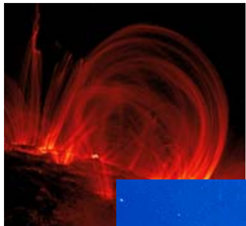
❑ Measurements

- ➢ Ultra-high (0.02 arcsec/pixel) EUV coronal imaging
- ➢ High resolution (0.1 arcsec/pixel) EUV/UV spectroscopy
- ➢ X-ray imaging spectroscopy (1 arsec/pixel, $\lambda/\Delta\lambda \approx 500$ @ 1 keV, msec time resolution)
- ➢ Multi-wavelength EUV/UV intermediate scale imager (0.1 arcsec/pixel)

RAM: Deployed Configuration



Summary

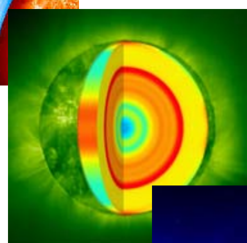


Solar-B [2005] – ISAS

High resolution magnetic field

STEREO [2005] – NASA

Out of Sun-Earth line, 3-D, CMEs



Solar Dynamics Obs. [2007] – NASA

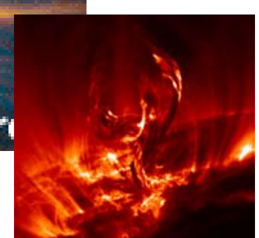
Magnetic field evolution – subsurface to corona – high time res.

Solar Orbiter [2011/12] – ESA

Out of ecliptic, far-side, co-rotation, inner heliosphere

Solar Probe / Sentinels – NASA ?

A closer look



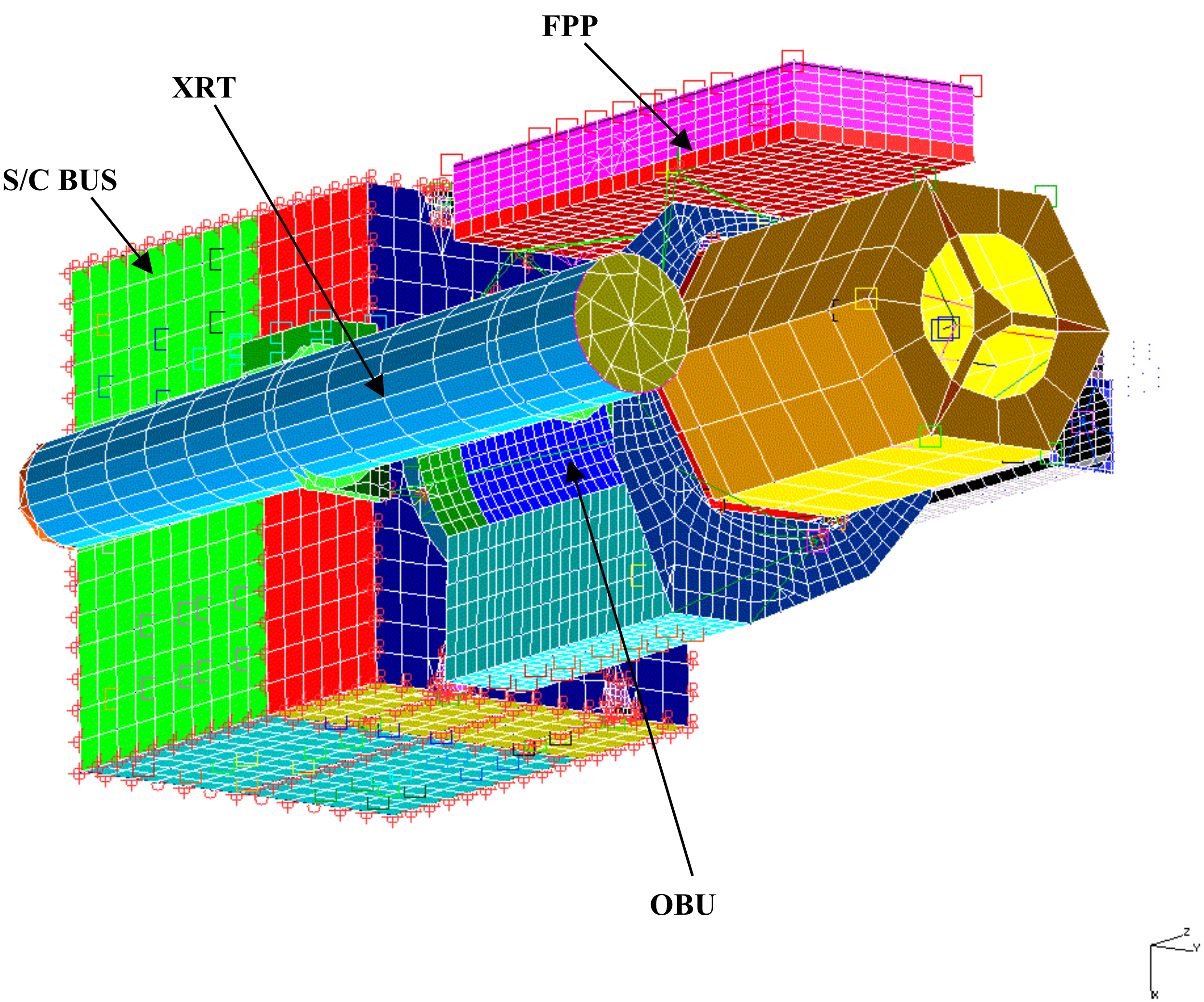
ASCE , RAM ? – NASA ?

corona, ultra high resolution

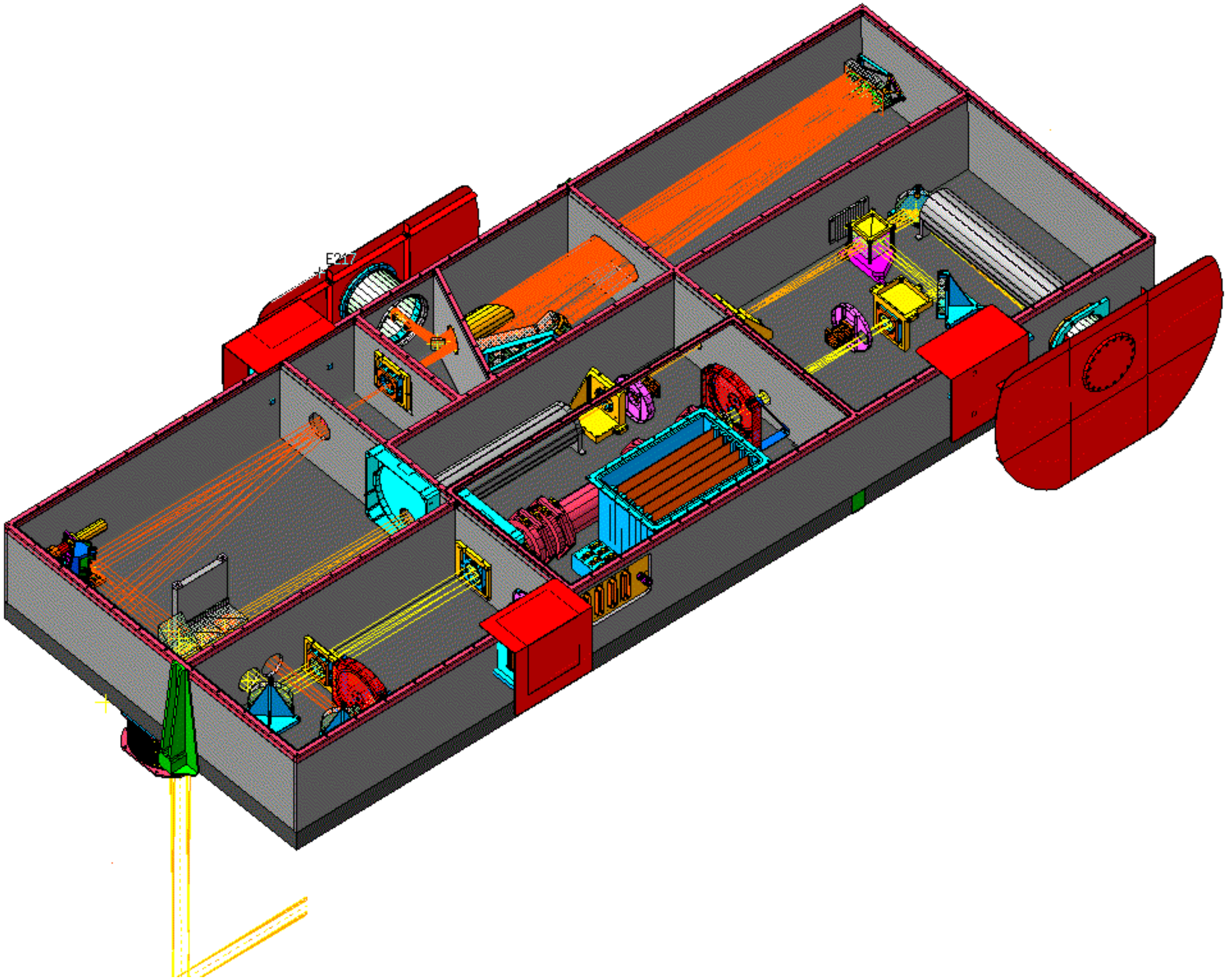
Prospects …

Prospects …

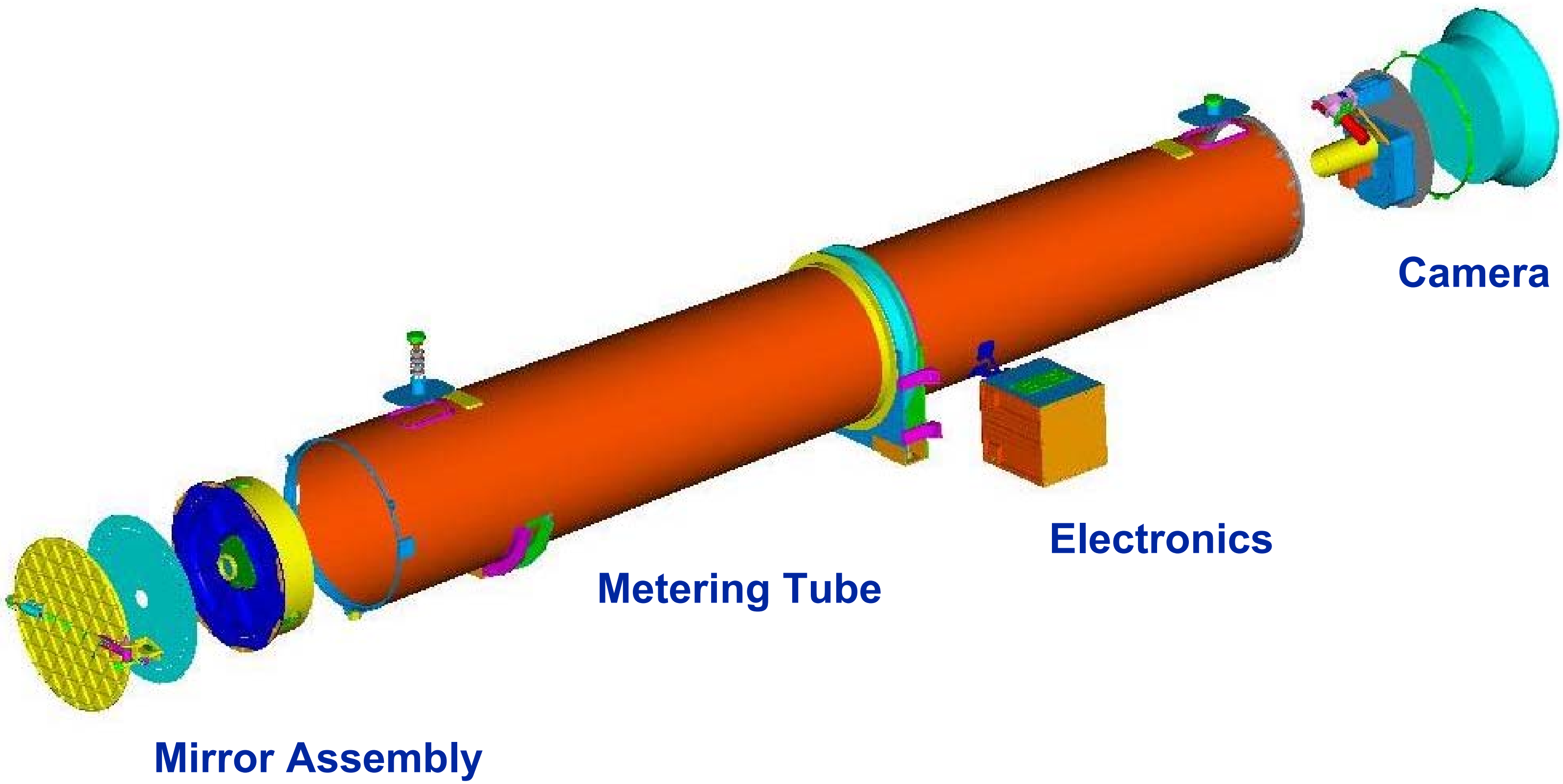
Solar-B: System Finite Element Model



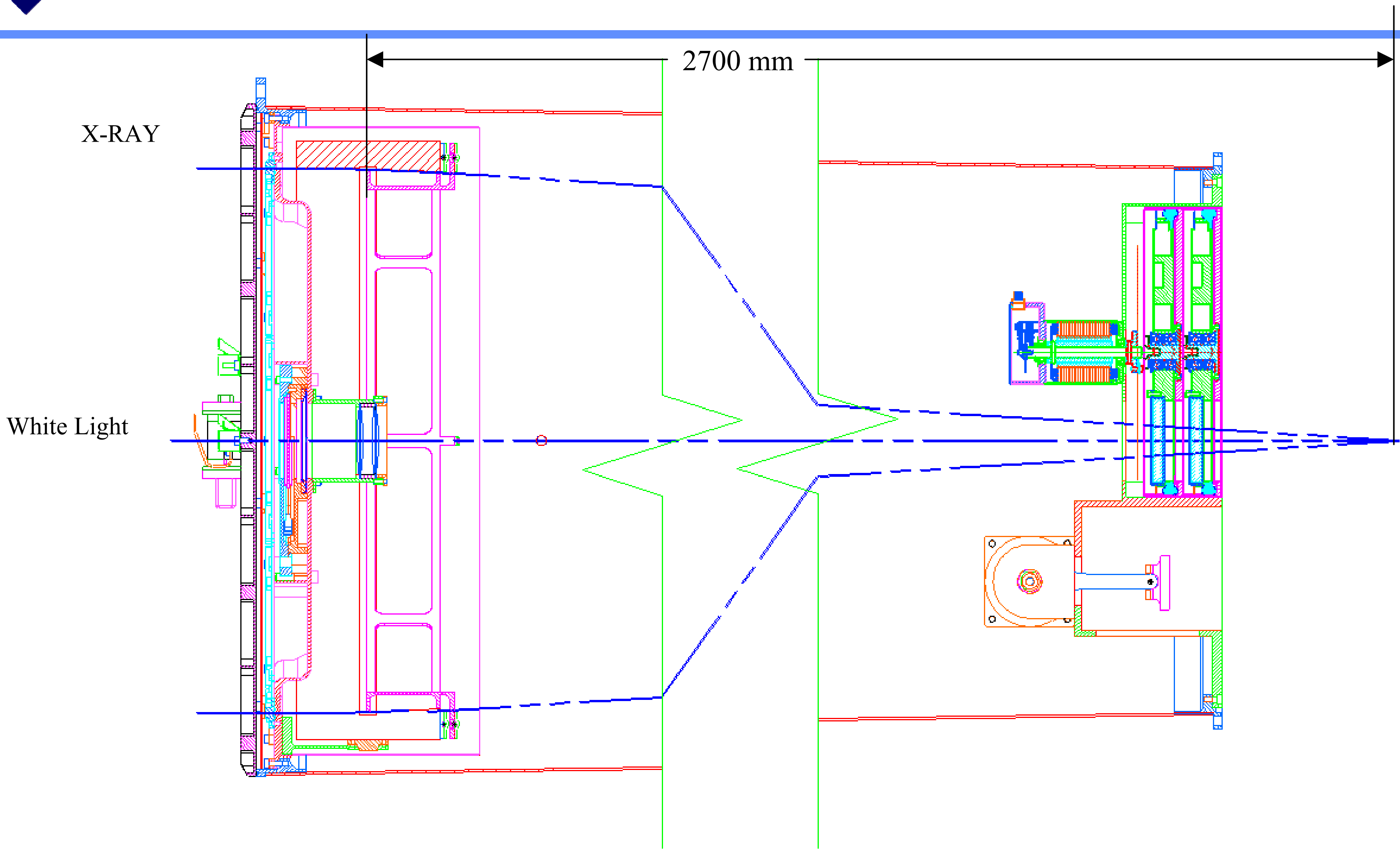
Solar-B FPP Design



Solar-B: XRT Schematics



Solar-B: XRT Optical Path

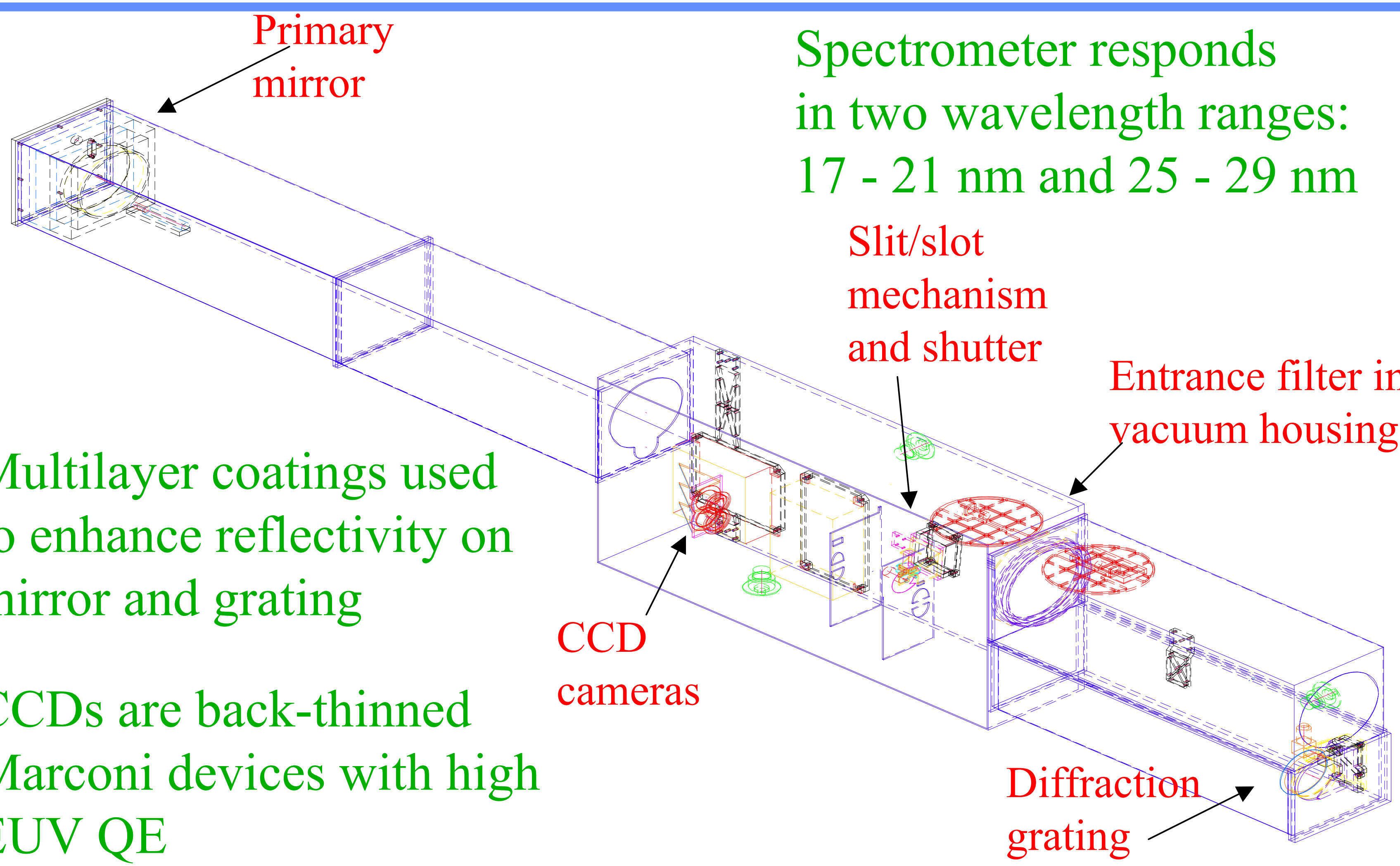


Solar-B: EIS Optical Layout

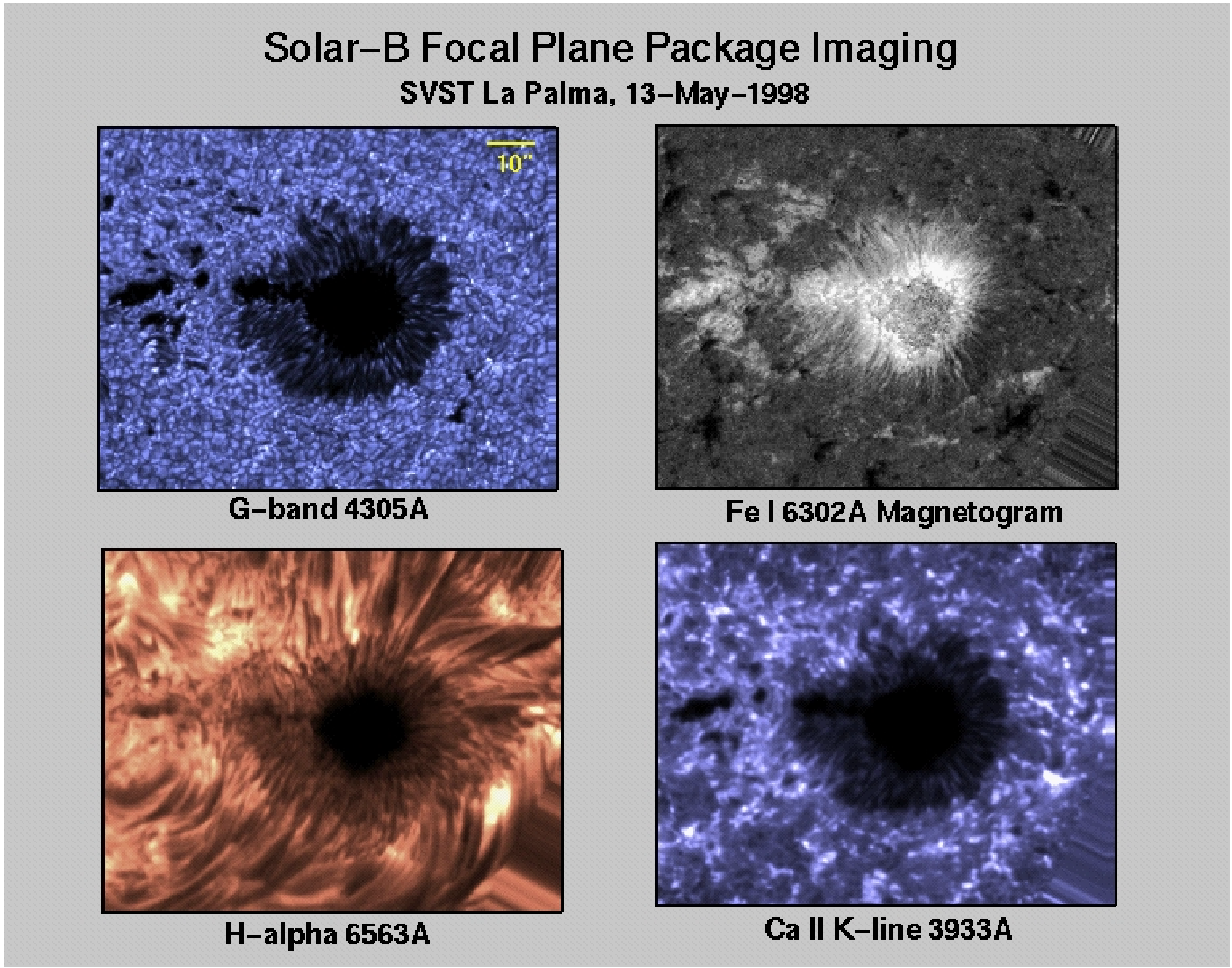
Spectrometer responds in two wavelength ranges: 17 - 21 nm and 25 - 29 nm

Multilayer coatings used to enhance reflectivity on mirror and grating

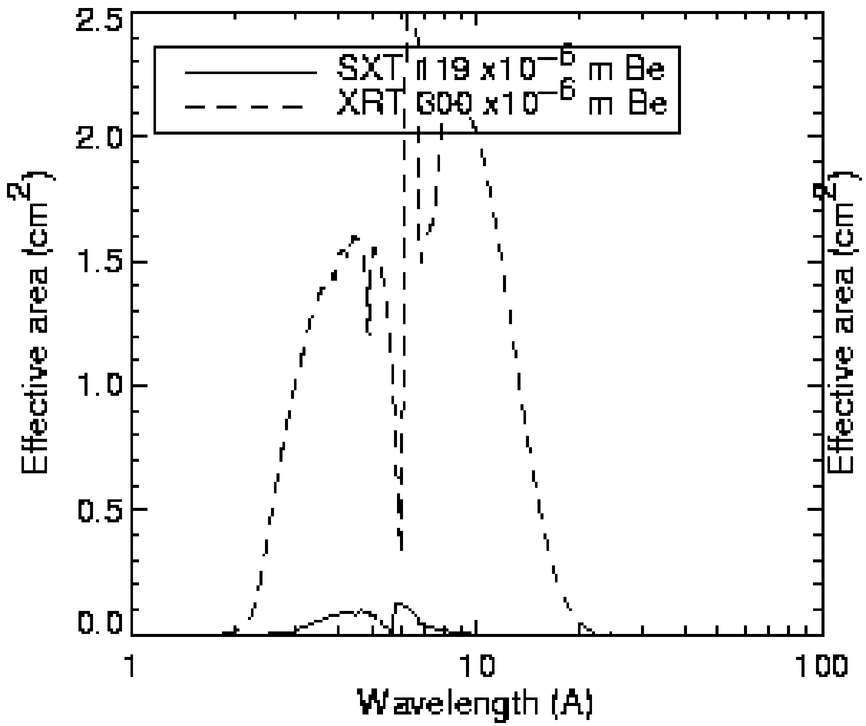
CCDs are back-thinned Marconi devices with high EUV QE

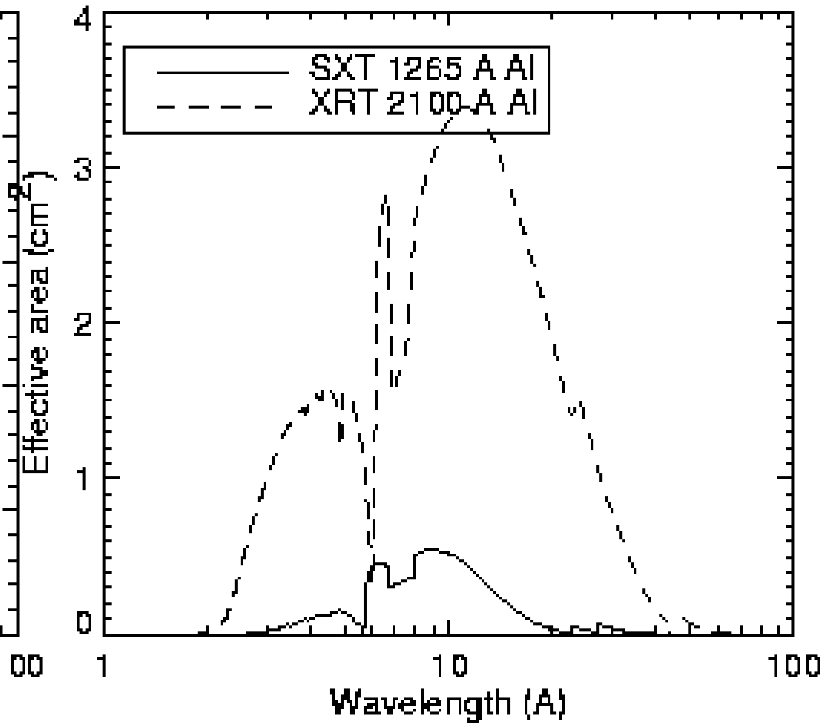


Solar-B: Sample FPP Data



Solar-B: XRT Effective Areas



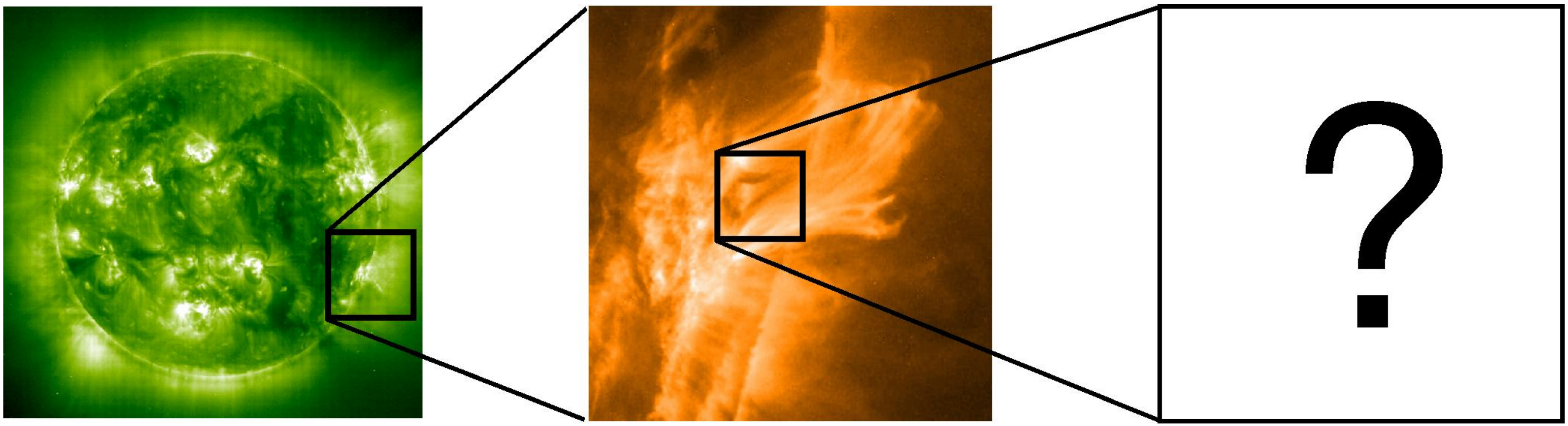


Solar Orbiter: Scientific Goals

- determine *in-situ* the properties and dynamics of plasma, fields and particles in the near-Sun heliosphere
- investigate the fine-scale structure and dynamics of the Sun's magnetised atmosphere, using close-up, high-resolution remote sensing
- identify the links between activity on the Sun's surface and the resulting evolution of the corona and inner heliosphere, using solar co-rotating passes
- observe and fully characterise the Sun's polar regions and equatorial corona from high latitudes

Solar Orbiter: Close-up Observations

- Imaging and spectroscopy, due to proximity, with an order of magnitude improvement over past missions

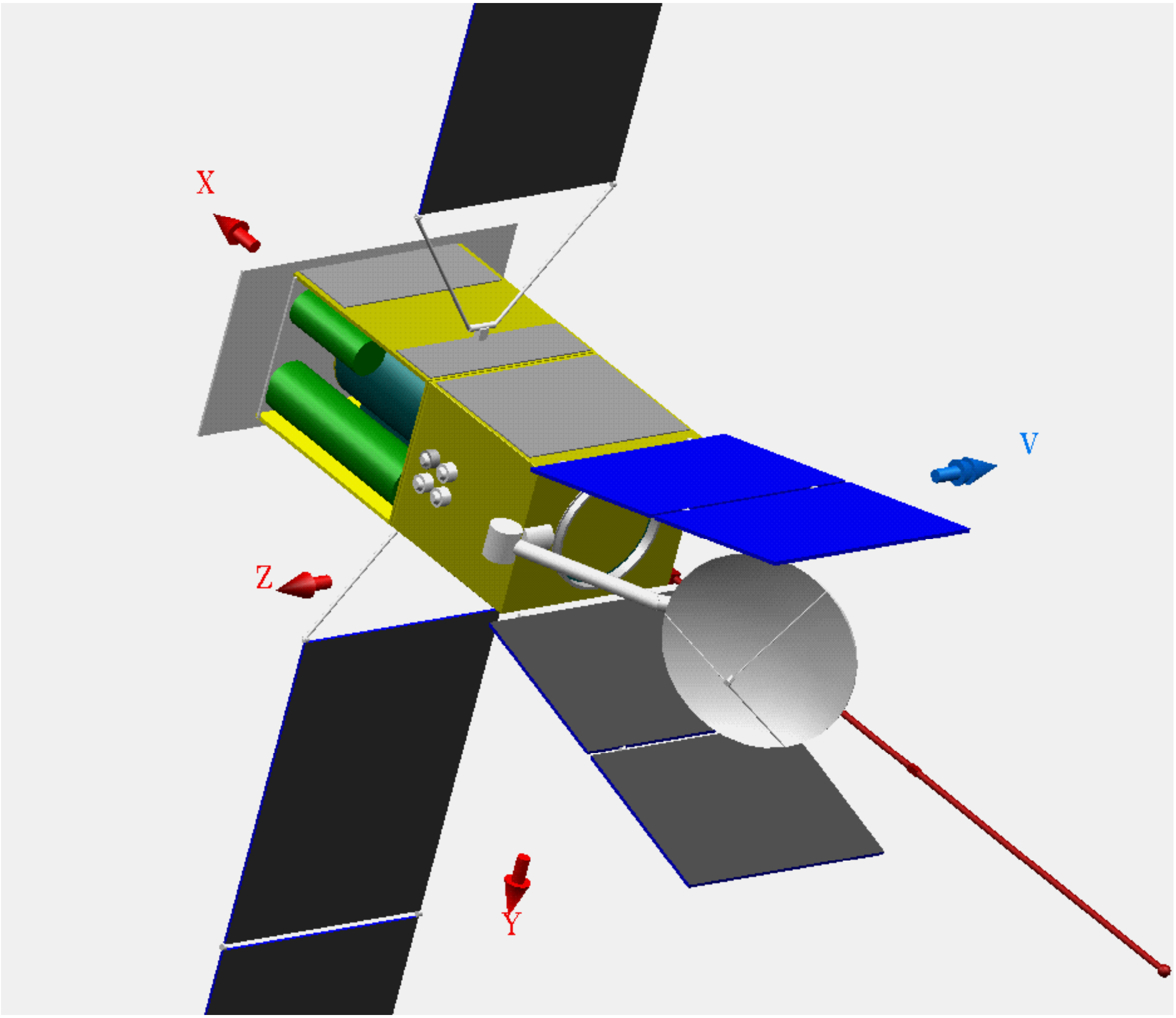


SOHO/EIT — **1850 km pixels**

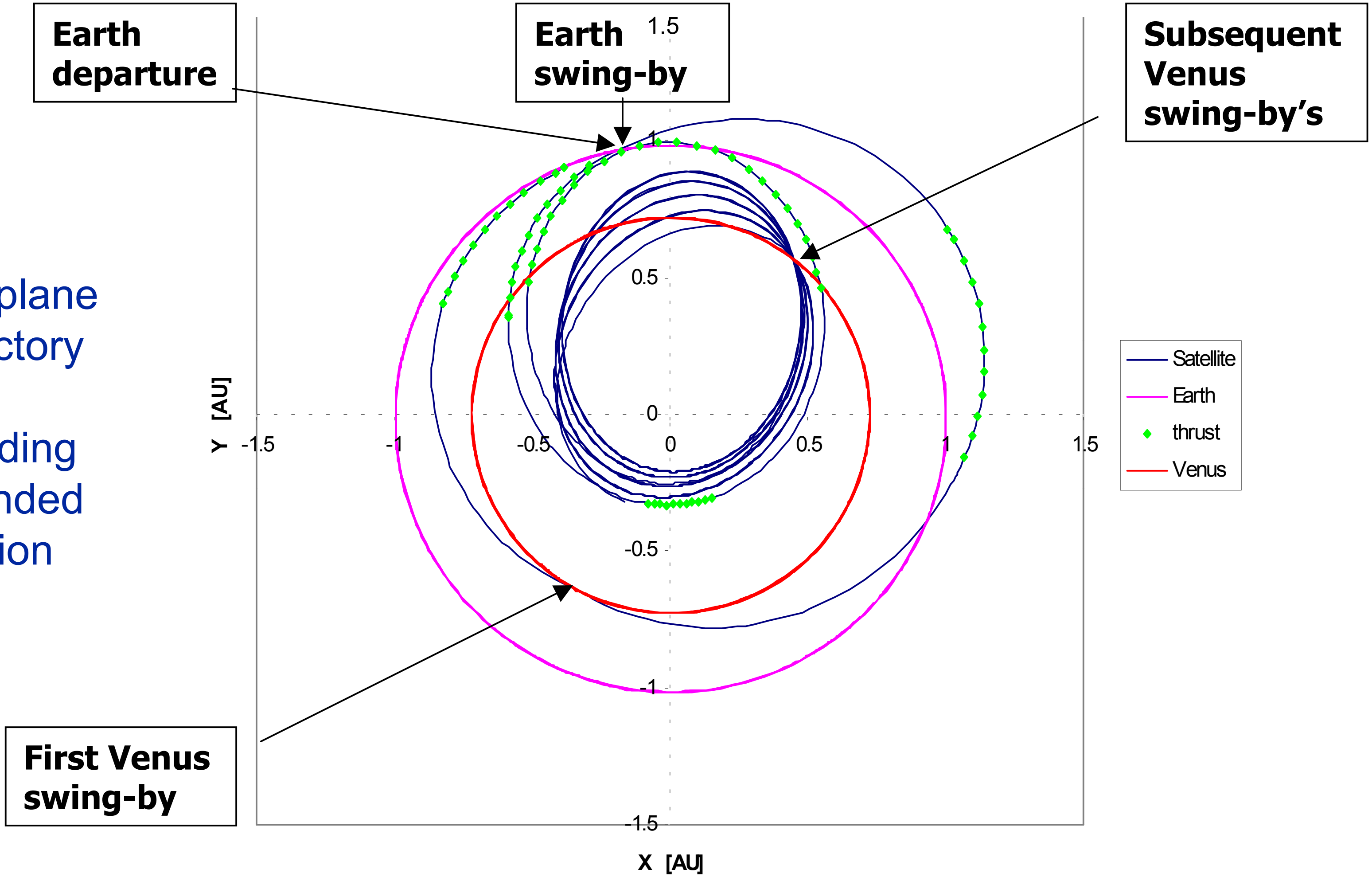
TRACE — **350 km pixels**

Solar Orbiter — **35 km pixels**

Solar Orbiter in Cruise Phase



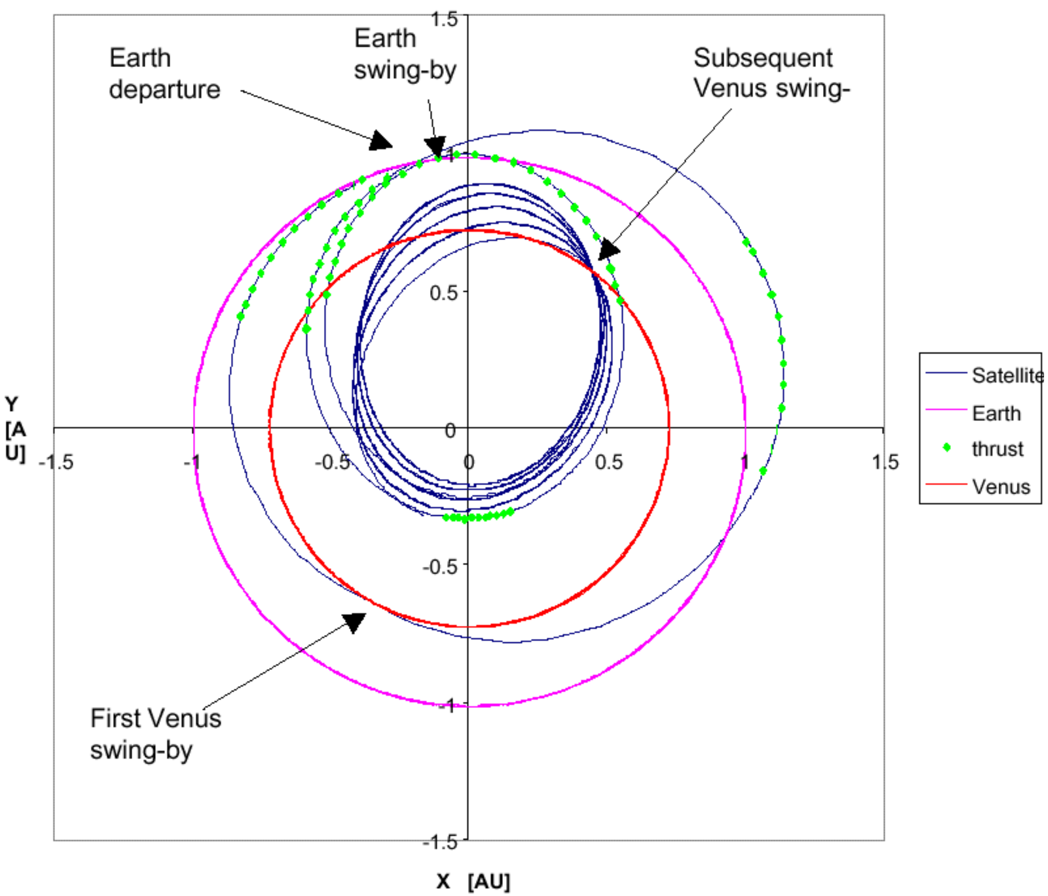
Solar Orbiter: Mission Phases



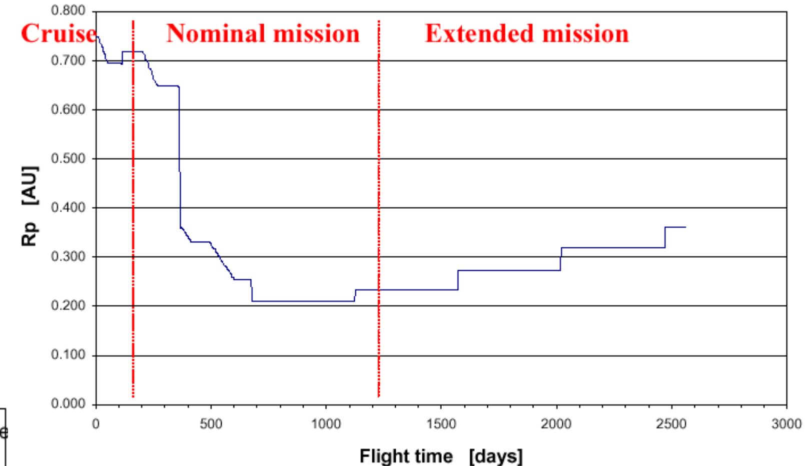
X-Y-plane trajectory plot including extended mission

Solar Orbiter Trajectory

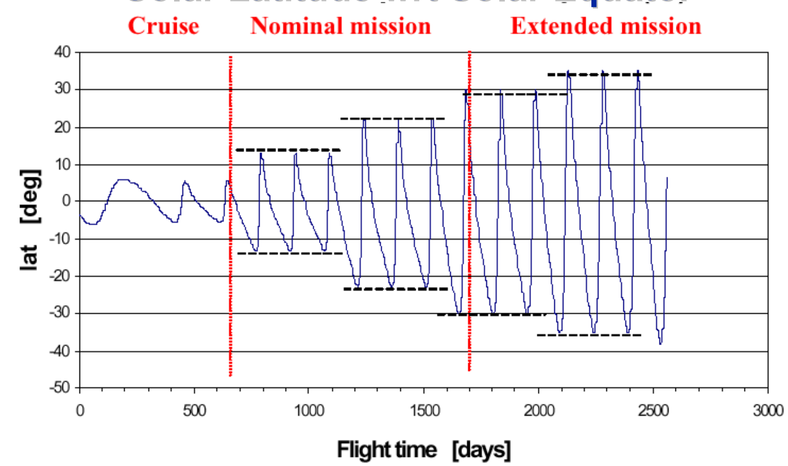
XY-plane trajectory plot including extended



Perihelion Radius



Solar Latitude wrt Solar Equator



Solar Orbiter: Spacecraft Design

- Mission lifetime: 4.7 years (extended 7.1 years)
- Solar aspect angle: 0° (Sun pointing)
- Spacecraft: 3-axis stabilised
- Observations: 30 days around each perihelion
- Lift-off mass: 1296 kg, with 130 kg payload
- Power: 7500 W, on cruise
  457 W, on nominal mission
- Science data rate: according to data dumping strategy
  (science data at 74.5 kb/s in observation, stored on 240 Gb on-board memory, dumped through HGA at max 750 kb/s)